THE DETERMINATION OF MINERALS UNDER THE MICROSCOPE

JOHN W. EVANS

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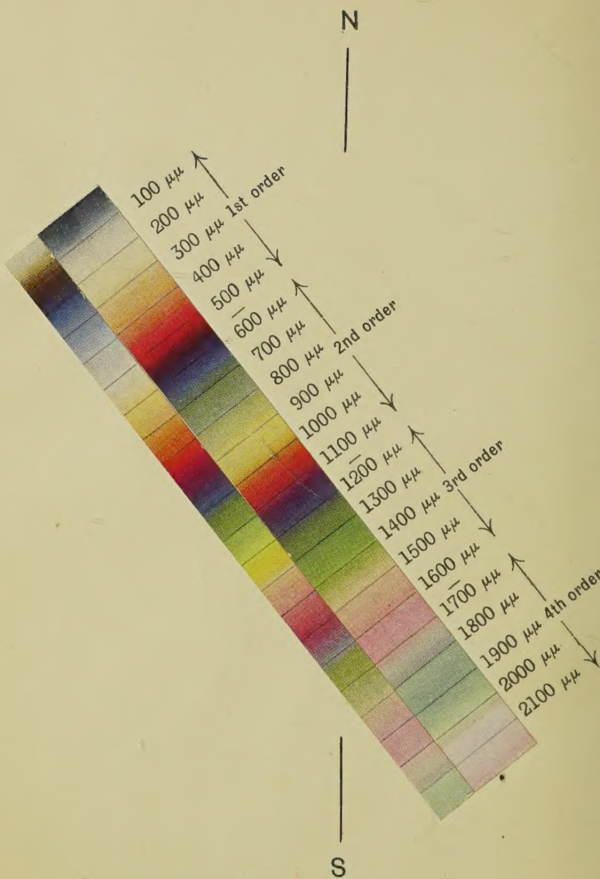

POLARISATION COLOUR SCALE

(By Dr. W. R. Jones and Dr. A. Brammall)

Wide slip gives colours between crossed Nicols:
Narrow slip gives colours between parallel Nicols:

Frontispiece. *Copyright.*

THE DETERMINATION OF MINERALS

UNDER THE MICROSCOPE

WITH SPECIAL REFERENCE TO THE
INTERPRETATION OF INTERFERENCE PHENOMENA

BY

JOHN W. EVANS
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PREFACE

THE following pages represent a revision and amplification of communications on the same subject published in the Proceedings of the Geologists' Association, 1909, vol. xxi., pp. 79-94, and in the *Journal of the Quekett Club*, 1915, vol. xii., pp. 597-630. They were written with a view of assisting students to realize the principles on which the optical study of minerals rest without the use of advanced mathematics. An excellent introduction to the use of the microscope in petrology has been provided by Mr. H. G. Smith, Lecturer on Geology at the East London College, which can be strongly recommended for the beginner. The present book has a different scope.

I have devoted special attention to the interpretation of interference phenomena on the lines traced out by Becke.

If any further explanation be required of references to crystallographical principles the student is referred to the book on "Elementary Crystallography" by myself and Mr. George M. Davies, London, 1924.

I have to thank Dr. Ingham, late of the Imperial College of Science and Technology, for reading the manuscript and for assistance with useful suggestions, and Mr. Frank Higham, B.Sc., of the same college, for preparing the illustrations, some of which are based, with the permission of the Council of the Geologists' Association, on the original illustrations that appeared in their Proceedings; some on illustrations to Rutley's "Rock-forming Minerals," published in 1888; and others are new. Mr. Higham has also rendered great service, during my absence abroad, in the revision of the

later proofs and preparation of the Table of Contents and the Index.

A second volume, dealing with the characteristics of individual minerals merely from the optical standpoint, is in a forward state of preparation, and, it is hoped, will be published in the near future.

J. W. EVANS.

EGYPT,
December, 1927.

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THE DETERMINATION OF MINERALS UNDER THE MICROSCOPE

I. THE PETROLOGICAL MICROSCOPE.

1. **Its Functions.** — The petrological microscope serves two distinct purposes. It is employed as an ordinary microscope to observe the form and relations of the more minute features of rocks and minerals, and it is at the same time designed for use as an optical instrument for studying the action of crystals on light with a view to their identification by this means. The latter function requires special features of greater or less complexity, which will be described in these pages.

If, however, it be desired to go further, and with the help of the microscope make exact determinations of the optical constants of substances that occur only in crystals so minute that the ordinary methods of research cannot be applied to them, this will naturally require a further elaboration of accessory apparatus of a special character, with which it is not now proposed to deal.

2. **As an Instrument employed for Magnification** the petrological microscope does not present any unusual features of importance. Like other microscopes, it consists essentially of an *objective*, which is a strongly convergent system of lenses, and the *eyepiece* or *ocular*. The more commonly used (" Huygenian ") ocular consists

of two convex lenses some distance apart. By the joint action of the objective and the lower *collecting* or *field* lens of the ocular a real image of the object is formed in a focal surface between the two lenses, and this is magnified by the upper lens (see Fig. 1).

3. **Illumination, Condenser**.—The object is usually examined by transmitted light, being illuminated from below by a mirror, one side of which is flat and the other concave, the latter causing the light to converge. This effect may be increased by the use of a condenser—a convex lens or system of lenses inserted below the stage.

Arrangements are usually made by which the condenser can be thrown in or out of the optical axis of the microscope, or its convergent effect on the illumination increased or diminished by its elevation or depression, or by the addition or removal of one or more lenses. Sometimes the same result is obtained by the substitution of one condenser for another.

The best illumination is that from the sky. If artificial light must be resorted to, a gas mantle provided with a screen of bluish glass, ground so as to be translucent but not transparent, or a small arc light similarly treated, may be employed. A "gas-filled" Osram daylight bulb also gives satisfactory results. If, however, the illumination is very strong, the lower nicol may be injured by over-heating. If there is any danger of this, a suitable glass vessel containing water or a dilute solution of copper sulphate may be interposed. The latter would replace the screen of bluish glass.

4. **Objectives.**—The objective most commonly employed is a 1″ (22 mm.), with a $\frac{1}{4}$″ (6 mm.) for more detailed work. Higher power objectives are not so frequently resorted to in petrological as in biological work, but there are many occasions in which a twelfth or a fourteenth may be usefully employed. High-

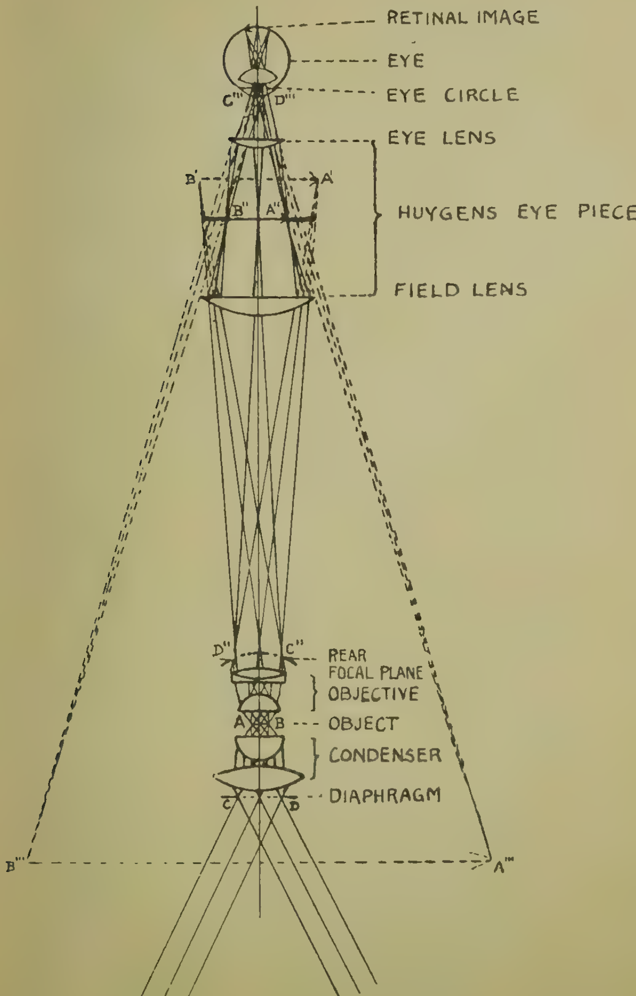
RETINAL IMAGE
EYE
EYE CIRCLE
C'''
D'''
EYE LENS
B'
A'
B''
A''
HUYGENS EYE PIECE
FIELD LENS
D''
C''
REAR
FOCAL PLANE
OBJECTIVE
A
B
OBJECT
CONDENSER
DIAPHRAGM
C
D
B'''
A'''

FIG. 1.

power objectives are also required for certain optical investigations.

It is often necessary to change quickly from one objective to another. To effect this without the delay of unscrewing one and screwing on another in its place, a nosepiece carrying two or three objectives is frequently employed. This is pivoted on an axis in such a manner that the objectives can be rotated in turn into the axis of the microscope. This nosepiece is, however, apt to get out of order, especially in the hands of students. The use of a clutch, first introduced by Nachet, by which objectives can be rapidly attached or removed, is preferable. Recently a lateral sliding arrangement has been introduced, which is equally convenient. In another the objective is attached, as usual, by means of screw action, but the thread is interrupted in alternate quadrants, both in the objective and on the body of the microscope, so that the objective can be pressed home at once and then secured by a quarter turn. Whichever apparatus is employed, it should be so adjusted that if one objective is in focus, that which replaces it will be found to be so likewise.

5. **Horizontal Movements.**—A mechanical stage which can be moved by means of screw action in two directions at right angles to one another and to the axis of the microscope is a great convenience. It should be provided with accurate graduation for effecting measurements and registering the position of points of interest in a microscopic slide. It will enable different portions of an object to be examined without change in the orientation relatively to the stage of the microscope. This is frequently a very important consideration in the study of the optical characters of minerals.

The graduations should with the aid of a vernier, or otherwise, read to 5 microns. A micron (μ, " mu ") is the thousandth part of a millimetre, 0·000,04 of an inch, and

is the most convenient unit of length for most microscopical purposes.

The dimensions of a crystal section in a rock slice may be measured by moving it across the field by means of the mechanical stage, so as to bring first one margin and then the other into coincidence with the intersection of the cross wires. The difference between the corresponding readings will give the intercept or width of the crystal section on a line through the intersection parallel to the movement.

A greater degree of accuracy may be obtained by the use of an eyepiece micrometer, the divisions on which must be carefully calibrated. This may be carried out by means of the mechanical stage. By the action of the screw movement the two end graduations on the scale of the micrometer are brought successively into coincidence with the intersection of the cross wires, and the difference between the corresponding readings of the mechanical stage is divided by the number of the divisions in the scale to give the value of each division.

If there is no graduated mechanical stage, a stage micrometer must be employed to calibrate the eyepiece micrometer.

The following procedure may be employed to determine the proportions by volume of the minerals present in a rock: A thin slice of the rock is moved across the intersection of the cross wires by means of one of the horizontal screw movements of the mechanical stage, and the amount of the intercept of each individual crystal is measured in the manner described. The slice should then be displaced a short distance by the second screw movement at right angles to the first, and a second traverse by the first screw movement would then be made. This should be repeated several times. The same process may then be carried out with the parts played by the first and

second screw movements interchanged. This is especially desirable if there be a parallel orientation of mineral crystals, which would otherwise erroneously affect the results.

The total length of intercepts obtained thus for each kind of mineral will be closely proportional to the volume of the mineral present in the rock, provided that the total length measured in the rock slice is at least one hundred times as great as the longest crystal intercept.

This method was suggested by A. Delesse,[1] but was first made generally known by A. Rosiwal.[2]

6. **Vertical Movements.**—The button of the fine-adjustment screw should be graduated on its circumference so as to show the number of microns by which the microscope is raised or depressed. By means of a vernier, or otherwise, it should be capable of being read to 5 microns. A complete turn of the screw will usually correspond to 500 microns, and in that case a scale parallel to the axis should be provided, divided into half-millimetres, so that by means of the double graduation comparatively large movements may be accurately measured.

7. **Rock Slices.**—The minerals examined by means of a microscope may either be studied in thin sections ground down with abrasives, or in the crushed fragments of a rock, or the constituent grains of a fine sand. The procedure in the former case will in the first place be exclusively considered.

It is unnecessary here to describe the process of the preparation of thin rock slices affixed to glass slips by means of Canada balsam, a transparent gum. As far as possible each slice should be uniform in thickness, which is secured by the Continental methods of grinding. In

[1] *Annales des Mines*, 4th series, vol. xiii., p. 388, 1848.
[2] *Verh. K. K. Geol. Anstalt*, Vienna, 1898, pp. 143-175.

this country, on the other hand, slices are usually thinner near the edges. This has its advantages where only one slice is cut, as it enables an examination of the rock in different thicknesses to be made; but it is more satisfactory to work with a number of slices, each of uniform thickness throughout its extent, but differing in thickness one from the other. A good rock slice should be between 15 and 30 microns (0·015 to 0·030 of a millimetre, or 0·0006 to 0·0012 of an inch) in thickness. Those of greater thickness are, however, occasionally desirable; and if still thinner slices of very fine-grained or opaque rocks could be obtained, they would for many purposes be of great assistance.

8. **Cover-glass.**—It is usual to use a cover-glass from 100 to 250 microns in thickness; but it is preferable that a rock slice intended for research should have no cover-glass, and that its surface and sides should be free from Canada balsam. It may then be covered in turn by liquids with different refractive indices or subjected to micro-chemical tests. When a rock slice is treated in this way it should be placed in a shallow glass dish with a flat bottom to prevent the microscope being clogged or injured by the liquids employed.

II. NATURE AND PROPERTIES OF LIGHT.

1. **Light in Crystals and Other Substances.**—The use of a petrological microscope as an instrument of optical investigation requires some knowledge of the properties of light in crystals. In opaque minerals, such as magnetite and most metallic sulphides and arsenides, light does not penetrate to any appreciable distance, and they must be studied by observing the manner in which light is reflected from their surfaces. This requires special appliances, which are provided in metallurgical microscopes. Such investigations are not within the compass of the present work, which is confined to the consideration of transparent substances. These fall into two main categories: *isotropic* substances, in which light has the same properties, especially the same velocity of onward movement at right angles to the wave front —"velocity of propagation," as it is usually called— whatever the direction of vibration; and *anisotropic* substances, in which the properties of the light, including the velocity of its advance, vary with the direction of the vibrations.

There is, however, another equally important distinction between isotropic and anisotropic substances. In the former the vibrations of light can take place in all directions parallel to the plane of the wave front. These movements do not, as a rule, consist of simple backward and forward swings in a straight line. For ordinary monochromatic light—that is to say, light of any one particular colour of the spectrum—they follow successively an endless variety of elliptical paths in the

plane of the wave front. In a single second there are millions of transformations in the form of the ellipses (which include as limiting forms a circle and straight line) and in the direction of their longer or major axes, and yet for thousands of repetitions the path traced is practically identical. This apparent contradiction is easily explained when it is remembered that there are nearly 400 million million vibrations of red light and about 760 million million of violet light in a single second. To realize what this means we may suppose time to be so greatly magnified that the period of vibration of violet light became equal to a second, then what had been a second would, on the same scale, be equal to more than 24 million years.

It follows that in the course of the smallest time perceptible to our consciousness—say a tenth of a second—the vibrations of ordinary monochromatic light in an isotropic medium take place in every possible direction in the plane of its wave front—that is to say, at right angles to the direction of its onward movement—and has therefore similar properties on all sides of its path. Such light is said to be unpolarized.

In anisotropic substances, on the other hand, light with a particular wave front can, as a rule, vibrate in two directions only, which are at right angles to one another. These lie, at least approximately, in the wave front and at right angles to its onward movement. Light vibrating in *one* of these directions is said to be polarized. In certain circumstances, even in isotropic media, light may vibrate in one direction only, and is to be considered as polarized (see *post*, p. 82).

Isotropic substances comprise vacuum—that is to say, empty space, gases, nearly all liquids, all non-crystalline solids, and all crystals belonging to the cubic system. Anisotropic substances, on the other hand, include all

crystals belonging to any of the other crystallographic systems, as well as cubic and non-crystalline substances that are in a state of strain.

2. **The Index of Refraction—Velocity of Light.**—The recognition of minerals in thin sections by means of their optical characters depends largely on a comparison of the refractive index of different minerals, and of different directions of vibration in the same mineral—that is to say, it depends on observation of the variation in the velocity of propagation of the light; for the index of refraction of light in a substance is equal to the ratio of the velocity of light in vacuum, which is constant, to the velocity in the substance; and, as this latter is always less than in vacuum, the index of refraction in any substance is always greater than unity. Thus, if ν be the index of refraction of certain vibrations of light in a particular substance, v the velocity of their advance in it, and v_0 the velocity of light in vacuum, $\nu = \frac{v_0}{v}$. The index of refraction of a substance is therefore proportional to the reciprocal of the velocity in that substance.

For practical purposes, so far as the optical work with microscopes is concerned, the air may be considered as indistinguishable from vacuum.

3. **The Indicatrix.**—It is found convenient to express the optical characters in any substance by means of a curved geometrical figure in three dimensions, which is known as an *indicatrix*. This varies in the form and size for different substances, and possesses the property that the length of any radius—that is, a straight line drawn from the centre to the surface—expresses the index of refraction of light vibrating in a direction parallel to that radius.

In a vacuum the indicatrix will be a sphere with radius unity (1 inch or 1 centimetre, or whatever unit

may be convenient), for the velocity and index of refraction are the same for all directions and all colours. In water the indicatrix will be a sphere with a radius about 4/3, the index of refraction of water, for the velocity is 3/4 of that in vacuum. As the velocity in all substances varies with the colour, being slightly less for violet than for red light, there will be a series of concentric indicatrices, one for each colour, that for violet being the largest, and that for red the least. For fluorspar, a cubic mineral, and therefore one in which the velocity is the same for all directions of vibration, the indicatrix will likewise be a sphere. For the yellow light of the sodium flame the index of refraction, and therefore the radius of the spherical indicatrix, will be 1·434; for sodalite, also cubic, it is 1·483. For Canada balsam, which is amorphous, and therefore isotropic, the radius is about 1·54; for red spinel, which is cubic, it is 1·717, and for diamond, also cubic, 2·4175. The index of refraction of the last-mentioned mineral is 2·465 for violet light, and 2·402 for dark-red light (line A). The velocity in the diamond is therefore little more than two-fifths of that in vacuum.

In the case of anisotropic substances the indicatrix is no longer a sphere, for the radii, being proportional to the indices of refraction of light vibrating parallel to them, vary in length in different directions. It is, in fact, an ellipsoid, a curved surface which possesses the property that, if it is cut by any plane, the resulting section has the form of an ellipse, or (but only in special cases) that of a circle; whereas every section of a sphere has a circular form.

The indicatrix has a characteristic form and orientation relatively to the crystal structure for each substance and for light of every colour of the spectrum. If this form and this orientation are known in any particular

case, it is possible to deduce from them the index of refraction of light vibrating parallel to any given direction, for it is, as already stated, equal to the length of the radius of the indicatrix parallel to that direction.

4. **The Section of the Indicatrix Parallel to a Wave Front.**—The indicatrix also enables us to ascertain the two directions, at right angles to one another, in which light with any particular wave front will vibrate; for these will be parallel to the greatest and least diameters of the ellipse formed by a section of the indicatrix through its centre parallel to the wave front. These diameters are at right angles, and constitute the major and minor axes of the ellipse. The corresponding semi-diameters, or radii, are equal to the refractive indices of the light vibrating parallel to them.

Let Fig. 2 represent such a section of the indicatrix for any particular colour. The major semi-diameter OT of the ellipse will be equal to τ ("tau"), the index of refraction of the light vibrating parallel to it, and the minor semi-diameter OS to σ ("sigma"), that of light vibrating parallel to that direction. The wave front of the light vibrating in each direction will travel onward at right angles to the section of the indicatrix—that is to say, at right angles to the plane of the drawing. Strictly speaking, the *light itself* does not as a rule travel in a direction exactly at right angles to the wave front, but the *wave front* may be considered to do so, and it is the direction of the movement of the wave front that is important for the present purpose. Accordingly, when the direction of the movement of light is referred to, it will be the direction at right angles to the wave front. The vibrations parallel to OS will have the greater velocity of advance, and those parallel to OT the less velocity. OS may therefore be referred to as the fast direction and OT as the slow direction; but it must be

remembered that in each case the words "fast" and "slow" refer not to the movement in the vibrations parallel to OS and OT respectively, but to the rate of advance of the light in a direction at right angles to both and to the plane of the section of the indicatrix. The directions OS and OT are frequently described as

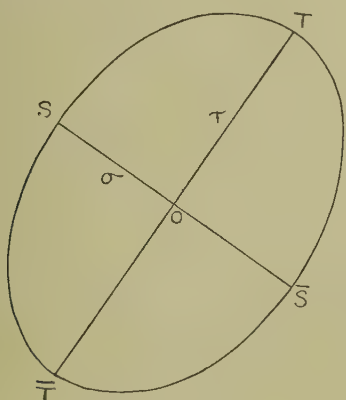

FIG. 2.

negative and positive respectively, because OS or σ is smaller than OT or τ.

5. **Vibration of Light in a Crystal Section.**—If a thin section of a crystal of an anisotropic mineral in a rock slice be placed on the stage of a microscope and examined under ordinary conditions, the light from the mirror will traverse it in a direction practically at right angles to the plane of the slice, so that its wave front is practically parallel to that plane; for the plane of the slice is at right angles to the optical axis of the microscope, and the deviation of the path of the light from parallelism to this axis, due to the microscope lenses, does

not substantially affect this assumption, unless exceptionally powerful lenses are employed.

Accordingly, when the light has entered such a crystal section it will in general, instead of vibrating in turn in all directions in its wave-front, be constrained to vibrate in two directions only, which are at right angles to one another—that is to say, those parallel to the major and minor axes of the elliptical section of the indicatrix which is parallel to the rock slice and the crystal section contained in it.

6. **Birefringence of a Crystal Section—Relative Retardation.**—The indices of refraction of the light vibrating in these directions will, as we have seen, be σ and τ, the lengths of the semi-axes OS and OT; and the difference $\sigma - \tau$ between them is known as the birefringence, or double refraction of the crystal section. If l be the length of the path in the crystal section—in other words, the thickness of the latter—the distance that would have been traversed by the light in vacuum, in the *same time* as that taken by the light vibrating parallel to OT in traversing the thickness of the section, would have been lv_o/v_t, where v_o is the velocity of light in vacuum and v_t the actual velocity of light vibrating parallel to OT in the crystal section. But v_o/v_t is equal to the index of refraction, τ, of the light vibrating parallel to OT (see p. 12). So that the distance that would have been travelled in vacuum is $l\tau$. Consequently, by traversing the crystal section instead of vacuum the light vibrating parallel to OT has been retarded by the distance $l\tau - l = l(\tau - 1)$. Similarly, the light vibrating parallel to OS has been retarded a distance of $l(\sigma - 1)$, where σ is less than τ. The retardation of the slow vibration parallel to OT relatively to the fast vibration parallel to OS will therefore be $l(\tau - 1) - l(\sigma - 1) = l(\tau - \sigma)$. This quantity is known

as the *relative retardation* of the crystal section, for the light of the colour employed, and may be distinguished by the letter k.

If the thickness l be equal to unity, the relative retardation will be equal to $\tau - \sigma$, which is, as we have seen, the birefringence of the section. This amount may be expressed for brevity by δ. If, therefore, light passes through a thin section of an anisotropic mineral in a direction at right angles to its plane, the retardation, k, of the slow vibrations relatively to the fast vibrations of light of any particular colour will be equal to the birefringence of the section $\tau - \sigma$, or δ, multiplied by the thickness of the section l.

As the form and relative magnitude of the major and minor axes of the elliptical section of the indicatrix vary with the orientation of the section and with the colour, the birefringence and the relative retardation will vary correspondingly.

The indicatrices of anisotropic minerals and other crystal substances belong to one or other of two main types—those of uniaxial and of biaxial crystals.

7. **Uniaxial Crystals.**—These include substances crystallizing in the tetragonal or hexagonal system.[1] All of them have indicatrices which are ellipsoids of revolution about the vertical axis of the crystal—that is to say, they are shaped as if they had been turned in a lathe round it (Figs. 3 and 4). A section at right angles to the vertical axis, and therefore parallel to the basal plane of the crystal, will be circular in form; and since all the radii in that plane are equal, there is no major or minor axis, and there is no reason why light traversing such a thin section at right angles should vibrate more in one direction in that plane than in another. If, when

[1] See Evans and Davies, "Elementary Crystallography," chaps. xii. and xv.

it entered the thin section, it was vibrating in all directions successively in the manner already described as typical of isotropic media, it will continue to do so. The birefringence of such a thin section will obviously be zero, for the radii of the corresponding section of the indicatrix being all equal, all the vibrations in that plane must have the same velocity and the same index of refraction.

Light traversing a basal section at right angles will therefore behave exactly as if the section were one of an isotropic substance. The path pursued by the light under these conditions, parallel to the vertical axis of the crystal, is known as the principal axis of optical symmetry, or as the *optic axis*, and as it is a unique direction in the crystal the latter is said to be *uniaxial.*

It will be seen later that in biaxial crystals a distinction is drawn between an optic axis and an axis of optical symmetry, but in uniaxial crystals the vertical axis corresponds to both.

If, however, the section be cut so as to be slightly inclined to the base, it will no longer yield a circular section of the indicatrix, but an elliptical section, with one axis parallel to the basal plane and the other inclined to it. The light traversing it at right angles will therefore vibrate in two directions in the plane of the section—one parallel to the basal plane and the other at right angles to the first and inclined to the basal plane. The corresponding refractive indices will differ slightly, and there will be a low birefringence. As the inclination of the section to the basal plane is increased, the difference between the axes of the elliptical section, and therefore the birefringence, will also increase till it reaches a maximum when the section is at right angles to the base and parallel to the vertical axis.

To resume: In every section, which is not parallel to

the basal plane, there will be one direction of vibration parallel to the basal plane and another at right angles to the first and making a right or oblique angle with the basal plane. The former has the same refractive in every case, however the section may be cut, and its vibrations are said to be *ordinary*. The latter has an index of refraction, which is dependent on the angle between the section and the basal plane, and its vibrations are therefore described as *extraordinary*. If the section be at right angles to the basal plane, the extraordinary vibrations will be parallel to the vertical axis, while the ordinary will, as usual, be parallel to the base. The birefringence will then be at a maximum. If the section be parallel to the basal plane, the ordinary vibrations will take place in all directions in it, and the birefringence will be zero.

In some uniaxial crystals (Fig. 3) the indicatrix has the form of a prolate spheroid approximating (in an extreme case) to the shape of an egg. In such a case the greatest radii, OZ, $O\overline{Z}$, are parallel to the principal axis, $ZO\overline{Z}$, while the smallest radii, OX, $O\overline{X}$, etc. (all equal to one another), are those parallel to the base. The vibrations parallel to the vertical axis have accordingly the highest refractive index and the slowest velocity of transmission, and those parallel to the base the lowest refractive index and the greatest velocity. Such crystals may be referred to as *slow* or *positive*. The maximum refractive index, that of light vibrating parallel to the vertical axis, is indicated by γ ("gamma"), and the minimum, that of light parallel to the base, by α ("alpha"). The directions of vibration in a thin section cut parallel to the vertical axis will, as we have seen, be parallel to the vertical axis and to the base; their refractive indices therefore will be γ and α, and the birefringence of the section $\gamma-\alpha$. As this is the maximum birefringence of any section of the crystal, it

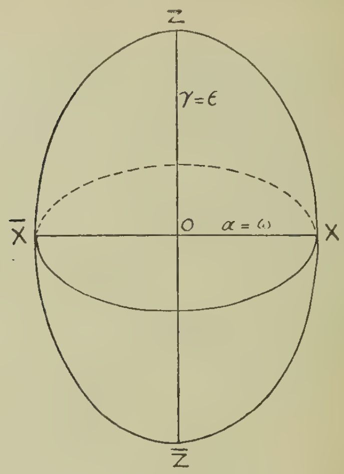

Fig. 3.

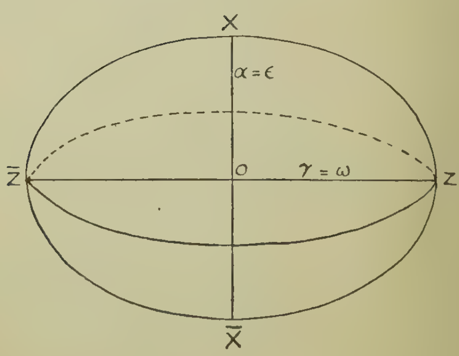

Fig. 4.

is known as the birefringence of the crystal. The average refractive index is taken to be equal to $(\gamma + 2\alpha)/3$.

In other uniaxial crystals (Fig. 4) the indicatrix is an oblate spheroid, like the earth. Here it is the minimum

radii, OX, $O\overline{X}$, of the indicatrix which are parallel to the principal axis, $XO\overline{X}$, whereas the radii, OZ, $O\overline{Z}$, etc., parallel to the base, are all equal and at a maximum. The vibrations parallel to the vertical axis have therefore the lowest refractive index and the greatest velocity. Such a crystal is therefore said to be *fast* or *negative*. The minimum refractive index, that of light vibrating parallel to the vertical axis, is now indicated by α, and the maximum, that of light vibrating parallel to the base, is γ. As before, the birefringence of the crystal will be equal in amount to $\gamma - \alpha$, but its mean refractive index is taken as $(\alpha + 2\gamma)/3$.

By some authors the index of refraction of light vibrating parallel to the base is always expressed by ω ("omega," for ordinary), and that parallel to the vertical axis by ϵ ("epsilon," for extraordinary). Consequently, in slow crystals $\epsilon(=\gamma)$ is greater than $\omega(=\alpha)$; while in fast crystals $\epsilon(=\alpha)$ is less than $\omega(=\gamma)$.

8. **Biaxial Crystals and their Birefringence.**—The indicatrices of crystals belonging to the remaining systems—the orthorhombic, the monoclinic, and the triclinic—are not ellipsoids of revolution either about the vertical axis or about any other line. Like ellipsoids in general, they possess the symmetry of the highest class of the orthorhombic system (the orthorhombic central class,[1] 11 Dc)—that is to say, they have a centre of symmetry, three planes of *optical* symmetry meeting in three digonal (or "half turn") axes of *optical* symmetry at right angles to one another. In crystals belonging to the orthorhombic system, the three axes of *optical* symmetry coincide with the three *crystallographic* axes; in those belonging to the monoclinic system, one of the axes of *optical* symmetry coincides with the ortho-axis; while in the triclinic system there is

[1] See Evans and Davies, "Elementary Crystallography," chap. vi.

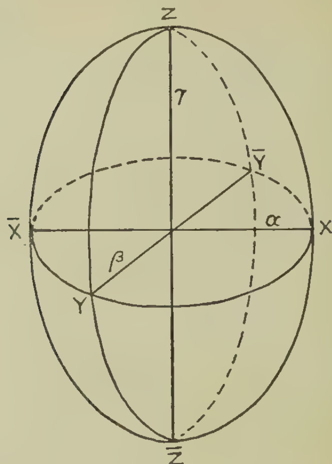

FIG. 5.

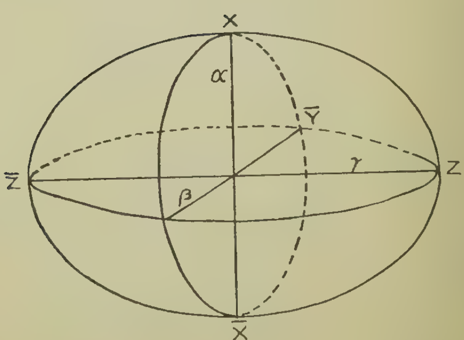

FIG. 6.

no simple relation between the axes of *optical* symmetry and the *crystallographic* axes.

One of the axes of optical symmetry, *ZOZ* (Figs. 5 and 6), is that of the vibrations with the highest refractive

index, $\gamma = OZ$, and with the least velocity of advance. It is referred to as the *slow* or *positive axis*, or (for reasons that will appear) the slow *bisectrix*. Another axis of optical symmetry, $XO\bar{X}$, is that of the vibrations of least index of refraction, $\alpha (= OX)$, and of the greatest velocity. This is the *fast* or *negative* axis or bisectrix. The index of refraction of the remaining axis of optical symmetry, YOY, is intermediate in amount, and its index of refraction is indicated by β ("beta") $= OY$. The direction YOY is known as the *optic normal*.[1] It is at right angles to the plane $ZX\bar{Z}\bar{X}$, which includes the axes of optical symmetry with greatest and least refractive indices, and is known, for reasons that will appear, as the *optic axial plane*. The radii of the indicatrix that lie in this plane show every gradation from the maximum, $\gamma = OZ$, to the minimum, $\alpha = OX$, so there will be two directions, $Y'O\bar{Y}'$ and $Y''O\bar{Y}''$, symmetrically situated with regard to one another and to the axes of optical symmetry, in which the radii are equal to $\beta = OY$, the index of refraction of the optic normal $YO\bar{Y}$ (see Figs. 7 and 8).

Now a plane passing through YOY and either $Y'O\bar{Y}'$ or $Y''O\bar{Y}''$ will cut the indicatrix in a curve which has equal radii at right angles to each other, and must therefore be a circle instead of an ellipse. There will thus be two circular sections of the indicatrix—that is to say, $YY'\bar{Y}\bar{Y}'$ and $YY''\bar{Y}\bar{Y}''$. The sections parallel to these directions will possess no birefringence, and the two directions $P'OP'$ and $P''OP''$, in which the wave fronts move at right angles to these planes, are known as the *optic axes*. Crystals with these optical characters are accordingly said to be *biaxial*. In dealing with biaxial crystals, the two optic axes must be carefully distinguished from the three axes of optical symmetry, but in uniaxial

[1] Unfortunately this term is occasionally used in the sense of the obtuse bisectrix (see pp. 23 and 24).

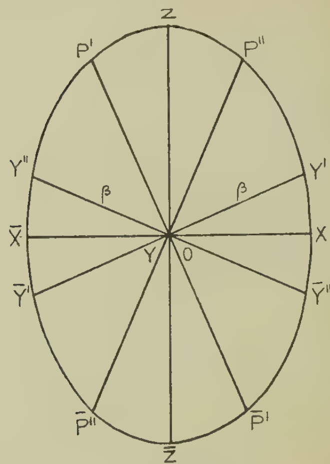

FIG. 7.

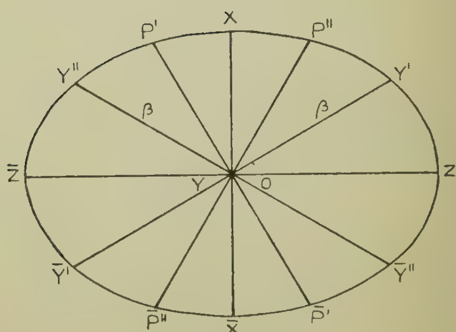

FIG. 8.

crystals the single optic axis coincides with the principal axis of optical symmetry.

The optic axes lie in the optic axial plane, and are symmetrically placed relatively to the directions $ZO\bar{Z}$

and $X O \bar{X}$, the axes of optical symmetry. The latter therefore bisect the angles between the former, and it is for that reason they are known as bisectrices.

The angle between the optic axes is known as the *optic axial angle.* It has two supplementary values: one of these is bisected by the slow direction $Z O \bar{Z}$, and the other by the fast direction $X O \bar{X}$. Either may be acute or obtuse. The bisectrix of the acute angle is known as the acute bisectrix (*bxa*), and that of the obtuse angle the obtuse bisectrix (*bxo*). If the acute bisectrix be $X O \bar{X}$, the crystal is described as *fast* or *negative* (Figs. 6 and 8). Similarly, if the acute bisectrix be $Z O \bar{Z}$, the crystal is said to be *slow* or *positive* (Figs. 5 and 7). If, exceptionally, the optic angle is a right angle, the crystal is *neutral*—neither fast nor slow.

When the optic axial angle is stated, it is usually the acute angle, and it then ranges between the limiting values 0° and 90°, the former corresponding to a uniaxial crystal, the latter to a neutral biaxial crystal; but sometimes the better plan is followed of always giving the angle bisected by the "fast" bisectrix $X O \bar{X}$, whether it is acute or obtuse, so that it varies from 0° to 180°, the former value corresponding to a fast uniaxial crystal and the latter to a slow one.

The angle between a bisectrix and an optic axis, which is half the optic axial angle, is usually written as V, and the optic axial angle as $2V$. The supplementary optic axial angles can be distinguished as $2V$ (fast) and $2V$ (slow), or $2V$ (acute) and $2V$ (obtuse). It can be shown that

$$\cos^2 V \text{ (fast)} = \alpha^2(\gamma^2 - \beta^2)/\beta^2(\gamma^2 - \alpha^2) = \tan^2\phi_\beta/\tan^2\phi_\alpha,$$

where ϕ_β and ϕ_α ("phi beta" and "phi alpha") are "auxiliary" angles employed for calculation by logarithms, and such that $\cos\phi_\beta = \beta/\gamma$ and $\cos\phi_\alpha = \alpha/\gamma$.

If the crystal be neutral, $2V = 90°$ and $\cos^2 V = \frac{1}{2}$; consequently, $\beta^2\gamma^2 + \beta^2\alpha^2 = 2\gamma^2\alpha^2$ or $\frac{2}{\beta^2} = \frac{1}{\gamma^2} + \frac{1}{\alpha^2}$, and β^2 is the harmonic mean between γ^2 and α^2.

The nearer β is to γ (relatively to α) the smaller is the fast optic axial angle, and the more the crystal approximates in its optical character to a fast uniaxial crystal. Similarly, the nearer β approximates to α (relatively to γ) the smaller is the slow optic axial angle, and the nearer the crystal approaches in optical character to a slow uniaxial crystal.

The crystal section that possesses the greatest birefringence in a biaxial crystal is that parallel to the optic axial plane, which has the two axes of optical symmetry, XOX and ZOZ, as the minor and major axes of its elliptical section of the indicatrix. Its vibrations are therefore parallel to these directions, and have the refractive indices α and γ. As the birefringence of this section, $\gamma - \alpha$, is greater than that of any other, it is considered to be the birefringence of the crystal.

The mean refractive index of the crystal is taken as the mean of those of the axes of optical symmetry, α, β, and γ—that is to say, $(\alpha + \beta + \gamma)/3$.

The descriptions which have been given of the indicatrices all refer, as already stated, to those of one particular colour of the spectrum. Every colour will have its own indicatrix. Those for violet will always be larger than those for red, but they will usually be similar in form. Occasionally, however, a crystal will have the fast bisectrix for one colour coinciding exactly or approximately with the slow bisectrix for another. Brookite, an oxide of titanium, is a well-known example.

9. **Relation of Cleavage to Optical Properties.**—The following relations generally prevail, but are not without exceptions:

(i.) Where there is a single well-developed cleavage plane, there is a fast axis of optical symmetry at right angles, or nearly so, to it.

(ii.) If there are two well-developed cleavages oblique to one another, there is a fast axis of optical symmetry bisecting, or approximately bisecting, the obtuse angle between them.

(iii.) If there are three well-developed cleavages oblique to one another, a fast axis of optical symmetry occurs in the centre of the obtuse trihedral angle.

(iv) If there are a number of cleavages with parallel intersections giving a mineral a fibrous structure, the direction of the fibres will be a slow axis of optical symmetry.

	Examples.	*Exceptions.*
(i)	Micas.	Brucite and some chlorites.
(ii.)	Hornblende.	Riebeckite.
(iii.)	Calcite.	—
(iv.)	Tremolite, anthophyllite.	Crocidolite.

III. EXAMINATION OF MINERALS IN POLARIZED LIGHT.

1. **The problem to be solved** in investigating the optical characters of a mineral in thin sections is in effect to ascertain the form and size of the indicatrix and its orientation relatively to the crystal structure. This may be ascertained with sufficient approximation by determining, with the help of the petrological microscope, the nature of the sections of the indicatrix corresponding to the different sections of the crystals of the mineral in the rock slices under examination.

The application of similar methods to small crystals, grains, or fragments will be described later (p. 102).

2. **Crossed Nicols.**—For the purpose of optical investigation, the slice containing the thin section is examined in *polarized light*, or, as it is sometimes expressed, *between crossed nicols*.

A *nicol*, or *Nicol's prism*, is a microscope accessory that only allows light vibrating in one direction to pass. When ordinary light traverses the uniaxial mineral calcite in any direction except parallel to the vertical axis, it is constrained, as we have seen, to vibrate in two directions at right angles to one another. In a Nicol's prism, however, the crystal has been cut through and re-cemented with Canada balsam in such a manner that the light vibrating in one direction passes through it, while that vibrating at right angles is reflected to one side by the Canada balsam and absorbed in the black mounting of the prism. The light which emerges continues to vibrate in one direction only, and is therefore said to be *polarized*.

One such Nicol's prism is inserted in the optical axis of the microscope below the stage on which the object is placed and another above it. The former is known as the *lower nicol* or *polarizer*, and the latter as the *upper nicol* or *analyser*.

As a general rule the nicols are so oriented that the direction in which vibrations of light are able to traverse one nicol is at right angles to that in which such vibrations can traverse the other. The nicols are then said to be *crossed*.

It is sometimes desirable that the nicols should be so oriented that the directions in which vibrations can pass them are parallel to one another. The nicols are then said to be *parallel*.

Polarized light, which vibrates in one direction only, is also developed when ordinary light (which vibrates successively in all directions in the wave front) is reflected at a surface separating two media. Such polarized light vibrates parallel to the reflecting surface and at right angles to the plane of incidence and reflexion. It is usually mixed with ordinary light; but if a pack or pile of thin glass plates is employed for the reflexion instead of a single plate, and is so placed that the wave front of the reflected light is at right angles to that of the light refracted in the glass, the polarization will be practically complete, and the pile of plates can be employed instead of a Nicol's prism; but it is not so convenient for use in a microscope.

3. **Cross Wires.**—In the focus of the ocular there are two cross wires at right angles to each other, one parallel to the direction of vibrations passing the lower nicol, and the other parallel to the direction of vibrations passing the upper nicol.

The cross wires should not be spider lines, which are easily broken by the insertion of the quartz wedge or

other accessories, but should be ruled on a glass plate. As this is apt to get covered with dust, the eyepiece should be made to screw apart immediately above the plate so that it may be easily cleaned. The cross wire can be focussed so as to be distinctly visible to the eye simultaneously with the object by screwing the upper lens of the ocular slightly in or out.

4. **Rotation of Stage or of Nicols.**—It is necessary for determinative work that it should be possible to vary the orientation of the section under examination relative to the directions of vibrations in the two nicols. This may be effected either by rotating the stage, with the section, or, the stage and section remaining fixed, by rotating the two nicols and the cross wires simultaneously by means of gearing. The former method has the advantage that the mechanism required is more simple and easily constructed; and the movements of the phenomena known as interference figures, which will be explained later, have been more carefully investigated and described as seen, when it is the stage that rotates than as seen in microscopes with rotating nicols. Microscopes with a rotating stage are quite satisfactory in all cases where the work is confined to thin sections placed at right angles to the axis of the microscope. On the other hand, for the examination of grains mounted in oil or other refracting medium, the use of a stationary stage and rotating nicols is practically a necessity if high-power immersion objectives are to be employed, unless the Nachet device is adopted, by which the objective is attached to the stage and rotates with it. Rotating nicols, too, are very desirable for the more complex optical methods, especially those that require one or more axes of rotation at right angles to the optic axis of the microscope, as when the optical characters of crystals in thin sections are studied by means of the theodolite stage, a subject

which is not dealt with here. It deserves consideration whether, when rotating nicols are employed, a rigid connection between them should not be substituted for gearing, even though the former is open to the objection that a rotation through a complete circle is not possible. This course has frequently been followed.

On account of their simplicity and comparative cheapness microscopes with a rotating stage and fixed nicols and cross wires are more frequently employed than those with rotating nicols; but the fact that the crystal structure in which the phenomena observed take place undergoes rotation is somewhat confusing to the student, and renders a systematic procedure, such as I shall describe, very desirable, if mistakes are to be avoided.

5. **Centring.**—The rotation of the stage necessitates arrangements to secure exact centring, so that the optical axis of the microscope may pass through the centre of rotation of the stage, otherwise the objective under examination will move out of the field as the stage is rotated. The mechanism for centring is operated by two screws at right angles one to another. It should be applied to the nosepiece and not to the stage, since it is the former which is liable to be displaced. This displacement is especially apt to occur if a double or triple nosepiece for interchanging objectives is employed.

In carrying out the operation of centring, a rock slice is placed in focus under the microscope, and the stage rotated. If the point in the slice round which the object seems to rotate does not coincide with the intersection of the cross wires, it is brought into that position by means of the centring screws.

6. **Rotation of a Single Nicol.**—Although in the ordinary microscope with a rotating stage the nicols are usually maintained in the same position, one or both of them should be capable of being rotated in certain con-

tingencies when it is desirable; but if a nicol is capable of separate rotation, it should receive a slight check by means of a catch or click when in the course of such rotating it comes into its normal position.

In microscopes with a fixed stage and rotating nicols it should also be possible to rotate one nicol separately.

When one nicol is rotated alone, it is usual to rotate the lower nicol; but this has been objected to on the ground that it may produce variation in the illumination on account of the partial polarization of the light received from the mirror and sky, and this variation might be attributed in error to the optical properties of the crystal section under examination.

7. **Position of the Nicols in the Microscope.**—The lower nicol is usually placed below the condenser. It must in any case be below the stage.

The upper nicol may be placed either low down in the tube of the microscope just above the objective, or above the ocular or eyepiece. The former position has the advantage of not obstructing the field, but there are two objections to this arrangement. In the first place, the nicol cannot, as usually constructed, be rotated; and, secondly, it does not allow of the insertion of a quartz wedge in focus, for, as will be seen, a quartz wedge must always be placed *between* the nicols.

Sometimes two upper nicols are provided, so that one can be inserted near the objective and one above the ocular.

8. **Removal of Nicols.**—It should be possible to throw either the upper or lower nicol rapidly out of the course of the light, so that the observation may, when desired, be made with one nicol only.

It is usual for this purpose to remove the upper nicol or analyser, but F. E. Wright recommends the removal of the lower nicol or polarizer. This has the advantage

that the field is not affected in focus or position when the nicol is moved in or taken out. For some purposes—as, for instance, if the light is defective—it may be desirable to remove both.

In the case of a nicol placed above the eyepiece, it should be capable of being thrown in or out by means of a hinge. A common practice by which it is removed altogether results in loss of time in adjustment when it is replaced.

The nicol that remains in position should be so placed that it allows light vibrating right and left to pass, for with the usual disposition of the mirror the light reflected from it is polarized, so that more of it already vibrates in this than in other directions. There is consequently an appreciable saving of light with this position of the nicol.[1] In the ordinary type of petrological microscope in use in this country the lower nicol, when in its normal position, allows the vibrations that are right and left in direction to pass, and it will be assumed in the following pages that this is the case.[2]

9. **Slots.**—The microscope should be provided with one or more slots for the insertion of various accessories. In this country slots are placed diagonally to the cross wires. On the Continent, however, they are sometimes arranged right and left. Accessories connected with polarization effects, such as quartz wedges, gypsum plate, or mica steps, must be constructed accordingly. This

[1] F. E. Wright, however, contends that it is only in the middle of the day that the arrangement recommended is advantageous, but in this country it is only then that the conditions of illumination are usually favourable.

[2] To ascertain in what direction light traversing a nicol vibrates the nicol should be inserted alone, and a rock slice containing biotite flakes showing strong pleochroism placed on the stage, and rotated till a flake is in the position of maximum darkness. The direction of cleavage of this flake will then be almost exactly parallel to that of the vibration in the nicol.

is a matter that requires attention in buying and using foreign microscopes. The slot is usually placed either immediately above the objective or in the focus of the ocular. F. E. Wright, however, prefers to have it below the stage (but naturally above the lower nicol), so that the insertion of a plate or wedge, like that of the lower nicol referred to above, does not affect the field. If the slot is above the stage, the best position is at the focus of the ocular, in which case the upper nicol must be placed above the ocular. This arrangement has the advantage that a quartz wedge and certain other accessories placed in the slot are in focus. If the slot is below the stage, the same result can be obtained by inserting the condenser, and raising or lowering it until any accessory in the slot is seen in focus at the same time as the object. A gypsum plate and similar accessories need not be in focus.

Means should be provided for closing the slot when not in use to prevent the entrance of extraneous light and of dust.

IV. PHENOMENA BETWEEN CROSSED NICOLS.

1. **General.**—It will now be convenient to consider the optical phenomena that are seen when a thin section of a crystal is placed between crossed nicols.

When light traverses the lower nicol, it is only the component part of the vibrations which can be resolved in the right and left direction (*i.e.*, parallel to the right and left cross wire) which will pass through. It is then, as we have seen, said to be polarized.

2. **Sections with Circular Sections of the Indicatrix**—(i.) *Isotropic Substances.*—If there is no anisotropic substance interposed the light will continue as it passes up the microscope to vibrate in the same direction, and will be stopped by the upper nicol, if the two nicols are crossed, for it can provide no component vibrating in a front and back direction (*i.e.*, parallel to the front and back cross wire), which alone can pass the upper nicol, and the result will be darkness.

(ii.) *Crystal Sections at Right Angles to an Optic Axis.*—The same will be the case if a thin section of a uniaxial mineral cut at right angles to the vertical axis and parallel to the base be interposed, as it also will not affect the direction of vibration of the light. A section at right angles to an optic axis of a biaxial mineral, and therefore parallel to the circular section of its indicatrix, will act in a similar manner, but for reasons into which it is not necessary to enter here a feeble light is in fact seen in this case.

3. **Rotational or "Circular" Polarization.**—These statements must be qualified in the case of crystals and

fluids possessing the property of circular polarization. When this exists, the direction of vibration of polarized light is rotated through an angle about the normal to the wave front. This angle is proportional to the length of path in the substance, but varies with the colour. A section of a crystal possessing this property cut parallel to a circular section of the indicatrix, will not be dark between crossed nicols, but in monochromatic light darkness can be obtained by rotating one nicol relatively to the other through a certain angle. For instance, light traversing in the direction of the axis a section of "right-handed" quartz cut at right angles to the optic axis will be rotated clock-wise—that is to say, in the direction of the hands of a clock, facing the direction towards which the light is travelling; and in "left-handed" quartz it will be rotated in the opposite direction. In the case of red light the rotation will be about 0·016 of a degree for each micron of thickness, in that of yellow sodium light 0·022 of a degree, and in violet light 0·051 of a degree. Consequently, in a typical section 25 microns thick the rotation will, except in the case of the most refractive vibrations, be less than a degree.

The effects of rotational or circular polarization are therefore practically not appreciable in the thin sections usually employed in petrological work.

4. **Crystal Sections Parallel to Elliptic Sections of the Indicatrix.**—We will now again consider the case of a thin section of an anisotropic mineral so cut that it corresponds to an elliptical section of the indicatrix, and assume that it is examined in monochromatic light.

(i.) *When Symmetrical to Cross Wires.*—If it is placed on the microscope stage, and the latter rotated into such a position that the major and minor axes of the ellipse are parallel to the cross wires (that is to say, to the directions of vibration of light which is permitted to pass

the lower and upper nicols respectively), the right and left vibrations that pass the lower nicol and reach the thin section will pass through it without change, because their direction of vibration will coincide with one of the two directions of vibration which are possible to light which traverses the thin section. They will therefore continue to vibrate in the same right and left direction and be entirely stopped by the upper nicol, which only

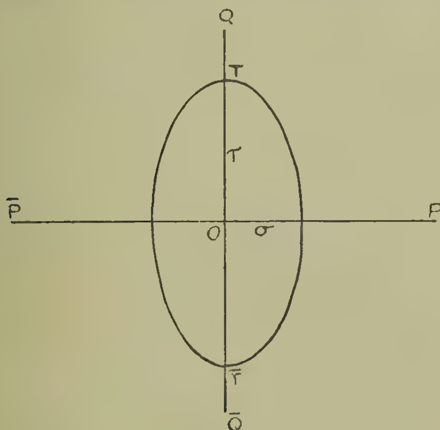

FIG. 9.

allows front and back vibrations to pass. See Fig. 9, where $P\bar{P}$ is the direction of vibration in the polarizer, $Q\bar{Q}$ that in the analyser.

(ii.) *When Oblique to Cross Wires.*—We will next suppose that the stage is rotated so that the major and minor axes of the elliptical section of the indicatrix are oblique to the two directions of vibrations in the lower and upper nicols, making angles of θ ("theta") and $\frac{\pi}{2} - \theta$ with them respectively, where π ("pi") signifies 180°,

(Fig. 10). Then any movement OP' due to the rectilinear vibrations parallel to the right and left cross wire, $P\bar{P}$, which pass the lower nicol will be resolved into two displacements, OT' and OS', along the directions of vibration, $T\bar{T}$ and $S\bar{S}$, in which the light is capable of vibrating in traversing the thin section—that is to say, parallel to the major and minor axes of the ellipse. Here $OT' = OP' \cos\theta$, and $OS' = OP' \sin\theta$.

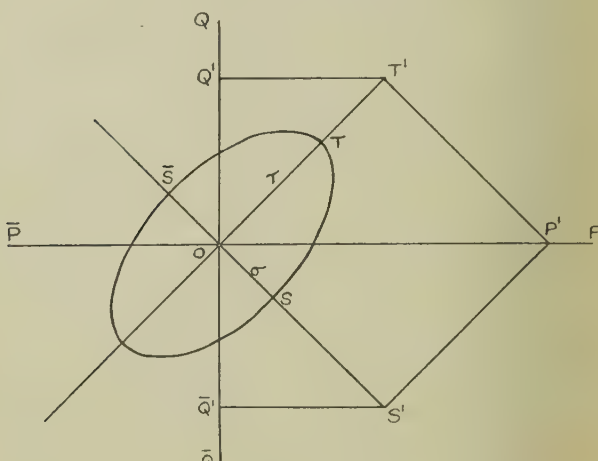

FIG. 10.

On reaching the upper nicol, however, only the components $OQ' = OT' \sin\theta$, and $O\bar{Q}' = OS' \cos\theta$, of these vibrations will pass—that is, the components which are parallel to the front and back cross wire. But OQ' and $O\bar{Q}'$ are opposite in direction and equal in amount, being each equal to $OP' \sin\theta \,.\, \cos\theta$.

5. **Effects of Relative Retardation.**—It would therefore appear at first sight that OQ' and $O\bar{Q}'$ would neutralize each other and we should have darkness as before; and

this would actually be the case if it were not for the fact that in the thin section the velocity of the vibrations parallel to TT' and SS' respectively are not identical, the vibrations parallel to TT' being retarded relatively to those parallel to SS. If the section is so extremely thin that the relative retardation is negligible, or if the amount of relative retardation is equal to a wave length or an exact number of wave lengths, there will be darkness. But if the relative retardation is equal to half a wave length or one and a half wave lengths, or any exact number of wave lengths plus a half wave length, the components OQ' and $O\dot{Q}'$ in the upper nicol will reinforce each other, and there will be the maximum of light. With intermediate amounts of relative retardation there will be different degrees of illumination.

6. **Birefringence, Thickness, and Relative Retardation.**—We have seen (p. 14) that the relative retardation, k (measured in vacuum or air) equals $l(\tau - \sigma)$, where l is the length of the path in the section—that is, the thickness of the section—and $\tau - \sigma$ or δ is the birefringence, the difference between the two refractive indices, and that this is equal to the relative retardation in a unit of length in traversing the crystal section.

7. **Quartz Plates and Quartz Wedges.**—If, for instance, a plate of quartz, cut parallel to the vertical axis, be 40 microns thick, the relative retardation for yellow sodium light, traversing it at right angles, may easily be calculated. Here the birefringence $\tau - \sigma = 1{\cdot}553 - 1{\cdot}544 = 0{\cdot}009$.[1] Hence the relative retardation in one micron (μ) will be 0·009 of a micron, and in 40 microns it will be $40 \times 0{\cdot}009$ microns $= 0{\cdot}36$ of a micron. It is, however, convenient to measure relative retardation in micromillimetres ($\mu\mu$), each equal to a thousandth part of a micron, and ten times the Angström units employed in

[1] More accurately 0·0091.

spectroscopic analysis. The relative retardation measured in micromillimetres in one *micron* will obviously be 1,000 $(\tau-\sigma)$, that is, in this particular case, 9 micromillimetres; and the relative retardation in 40 microns, will be 40×9 —that is, 360 micromillimetres. The amount 1,000 $(\tau-\sigma)$ (the relative retardation in micromillimetres per micron) may be referred to as the *birefringence in "millesims."* It has the advantage that it does not involve small decimal fractions. It is obtained by moving the decimal point in δ or $\tau-\sigma$ three places to the right.

The thickness of quartz, cut as above described, required to give a relative retardation of half a wave length of sodium light can be easily calculated, since it is known that half a wave length of this light measured in vacuum or air is equal to $\frac{589}{2} = 294{\cdot}5$ micromillimetres. Accordingly we have $294{\cdot}5 = l \times 9$, so that the thickness, l, will be equal to $294{\cdot}5/9$, or approximately 32·37 microns. A plate of that thickness will therefore be fully illuminated in the diagonal position in yellow light.

To obtain a relative retardation of one wave length of sodium light, the thickness of such a quartz plate would be $589/9{\cdot}1$, or about 64·74 microns. With such a plate there will therefore be no illumination. A quartz plate having a thickness of an exact multiple of this will also obviously be dark, and one with an additional thickness, in each case of $\frac{1}{2} \times 64{\cdot}74 = 32{\cdot}37$ microns, will be light. If, therefore, a wedge of quartz is cut with a low angle, so as to resemble a plate with parallel surfaces but with a gradually increasing thickness, it will show in yellow sodium light a succession of dark bands when the thickness is 65 microns or an exact multiple of that amount, with light intervals between, where it is an odd multiple of 32·37 microns.

8. **Sections in Different Directions.**—As we have seen, the birefringence varies considerably for plates cut in different directions in the same crystal and for the same colour, and the relative retardation will vary in a corresponding manner; hence plates cut in different directions will give different effects. The amount $\gamma - \alpha$ is the maximum birefringence for the crystal, and is, as already stated, given in uniaxial crystals by sections parallel to the vertical axis, and in biaxial crystals by those parallel to the optic axial plane. Sections parallel to other directions will have smaller birefringences and relative retardations.

9. **Light of Different Colours.**—Although sections parallel to the same direction in the same mineral have different refractive indices for different colours, they have as a rule approximately the same birefringence, and therefore approximately the same relative retardation; but as the relative retardation required to give complete reinforcement is a half wave length, and that to give complete darkness a whole wave length, the thickness required to produce these effects will be proportional to the wave lengths. But as the thickness of the quartz wedge is proportional to the distance along it, the distance between the bands will also be proportional to the wave length of the monochromatic light employed. For instance, if violet light having a wave length of 397 micromillimetres is transmitted through the quartz wedge, the distance between the centres of successive dark bands will be about half of that between the centres of the corresponding bands when red light having a wave length of 761 micromillimetres is employed. It is easily seen that the first light band will occur at a point where the quartz has a thickness of 22 microns in the case of violet light and 42 microns in that of red light, and the succeeding dark band where it has a thick-

ness of 44 microns in the case of violet light and about 84 in that of red light.

10. **Phenomena with White Light: Succession of Colours with Increasing Thickness of the Quartz Wedge.**—In the examination of thin sections white light is usually employed instead of monochromatic light. It may for our present purpose be regarded as a mixture of innumerable monochromatic vibrations. The alternating bands of light and darkness in the quartz wedge for each of the different colours will now be superposed and a series of mixed tints will result, which in most cases closely approximate to the interference tints usually referred to as Newton's colours, produced by the interference between the reflexions from the outer and inner surface of a thin film of transparent liquid.

If the wedge were ground so skilfully that its thin edge was completely preserved (which is, unfortunately, never the case) all the colours would have their first dark bands coincident at that point. As the thickness of the wedge gradually increases the short violet and blue waves begin to be visible, and a faint bluish-grey colour results. As the thickness is increased still more, these are reinforced by the other colours, and the grey passes into white, which extends from a relative retardation of about 230 micromillimetres to one of 265. Then a yellow tinge appears, due to the disappearance of the violet and blue in their second dark bands. Gradually the yellow deepens, and then passes from orange to red, the latter extending from about 510 to over 550 micromillimetres of relative retardation.

This completes what are known as the colours of the first order. They are succeeded by purple, violet, blue, green, yellow, orange, and red in turn, constituting the colours of the second order. These colours correspond to relative retardations from about 560 to 1,100. They are followed by the colours of the third order, a similar

succession, but more delicate in their shades because more complex in their composition, extending from about 1,100 to about 1,650. Each order is considered to terminate with the end of the red. The fourth, fifth, and subsequent orders, each corresponding to an increase of relative retardation of about 550, are progressively paler, and consist mainly of faint greens and pinks. When the seventh and eighth orders have been reached the colours have almost disappeared, and finally only white light is visible. It is scarcely necessary to add that none of these are true spectrum colours; they are merely mixtures of them.

If one of the nicols be rotated through 90 degrees, so that the directions of the vibrations that they permit to pass are parallel, the dark and light bands in monochromatic light will change places, so that the thin edge of a perfect wedge would show maximum light. With a white illumination the colours will commence with white light instead of darkness. This will be succeeded by yellowish and brownish white, brown, red, violet, blue, and yellowish green, these being complementary to the colours of the first order with the same relative retardation when the nicols are crossed. The colours corresponding to each of the second and third orders will commence with green followed by orange, red, violet, and blue. In the higher orders the general character of the colours with parallel nicols will be the same as those with crossed nicols, but the pinks and greens will change places. They will gradually fade away into white in the same manner as with crossed nicols. The colours with parallel nicols will only be truly complementary to those with crossed nicols when the quartz wedge is in the *diagonal position*, that is, when the directions of vibrations in it bisect the angles between those in the nicols. Otherwise colours with parallel nicols

will be mixed with white light. The nearer the directions of vibrations in the wedge approach those in the nicols the greater will be the proportion of white light, and when they coincide with them the light will be entirely white.

Relative Retardation in Micro-millimetres.	Thickness in Microns of Quartz Plate Cut Parallel to the Axis.	Crossed Nicols.	Parallel Nicols.
		First Order.	First Order.
0	0·0	Black	Pure white
40	4·4	Iron grey	White
97	10·7	Lavender grey	Yellowish white
158	17·4	Grey blue	Brownish white
218	24·0	Pale grey	Yellowish brown
234	25·7	Greenish white	Brown
259	28·4	White	Clear red
267	29·4	Yellowish white	Carmine red
275	30·2	Pale straw yellow	Dark reddish brown
281	30·9	Straw yellow	Deep violet
306	33·6	Clear yellow	Indigo
332	36·5	Bright yellow	Blue
430	47·3	Brownish yellow	Grey blue
505	55·5	Reddish orange	Bluish green
536	58·9	Red	Pale green
551	60·5	Deep red	Yellowish green
		Second Order.	Second Order.
565	62·1	Purple	Clear green
575	63·2	Violet	Greenish yellow
589	64·7	Indigo	Golden green
664	73·0	Sky blue	Orange
728	80·0	Greenish blue	Brownish orange
747	82·1	Green	Clear carmine red
826	90·8	Clear green	Purple red
843	92·6	Yellowish green	Violet purple
866	95·2	Greenish yellow	Violet
910	100·0	Pure yellow	Indigo
948	104·2	Orange	Dark blue
998	109·7	Bright orange red	Greenish blue
1101	121·0	Dark violet red	Green
		Third Order.	Third Order.
1128	124·0	Clear bluish violet	Yellowish green
etc.	etc.	etc.	etc.

11. The table of colours on p. 42 will be convenient for reference. Chromographic plates showing these colours, prepared by Dr. W. R. Jones and Dr. A. Brammall, will be found in frontispiece,[1] but in determining colours much depends on the idiosyncrasy of the observer and the character of the light. In the smoky atmosphere of a London winter, for instance, the blue of the second order under crossed nicols appears, as Mr. T. Crook pointed out to me, to pass directly into greenish yellow without anything that could be definitely characterized as green intervening.

12. **Conditions of Darkness between Crossed Nicols; Positions, and Directions of Extinction.**—We have seen that a thin section of a transparent mineral will be dark between crossed nicols in monochromatic light—

(i.) When the section of the indicatrix parallel to the thin section of the mineral is a circle—that is to say, when the mineral is isotropic or when the thin section is at right angles to an optic axis.

(ii.) When the section of the indicatrix is an ellipse, and its axes, and therefore the directions of vibration of the light in the mineral, are parallel to the directions of vibration in the nicols and to the cross wires.

These conditions will, in the course of a complete rotation of the stage, be fulfilled four times at intervals of 90°. Such positions are termed *positions of extinction*; and the directions in the crystal section which are then parallel to the cross wires are described as the *directions of extinction.*

(iii.) When the section of the indicatrix is an ellipse and the relative retardation is an exact multiple of a wave length.

[1] Published by James Swift and Son, Ltd., 81, Tottenham Court Road, London, W. 1.

13. **Extinctions in White Light.**—To obtain a complete extinction in white light it is necessary that the directions of extinction should be the same for all colours, or at least approximate very closely to one another. The directions of extinction can only be identical for different colours when the thin section is at right angles to a plane of optical symmetry which is identical for different colours. In uniaxial crystals this condition is always fulfilled, because every plane parallel to the vertical axis is a plane of optical symmetry. In other classes of anisotropic crystals a plane of optical symmetry is only the same for all colours when it is also a plane of crystallographic symmetry. In the orthorhombic system the three axes of optical symmetry coincide with the crystallographic axes, and the planes of optical symmetry coincide with the planes of crystallographical symmetry. In the monoclinic system only one axis of optical symmetry coincides with a crystallographic axis, and only one plane of optical symmetry coincides with a plane of crystallographic symmetry. In the triclinic system no axis of optical symmetry coincides with a crystallographic axis, and there are no planes of crystallographic symmetry.[1]

[1] In the classes of biaxial crystals in which there is a centre of symmetry there is a line of crystal symmetry (an axis of even symmetry) at right angles to every plane of crystal symmetry, and *vice versa*; but where there is no centre of symmetry, a plane at right angles to a line of crystal symmetry is not a plane of crystal symmetry. It will, however, have the same optical characters as if it were. In the II Du, orthorhombic uniterminal class of the orthorhombic system, there are two planes of crystal symmetry and one plane which is not a plane of crystal symmetry, but is at right angles to a line of crystal symmetry. In the II Mh, digonal holoaxial class of the orthorhombic system, there are three planes which are not planes of crystal symmetry, but which are at right angles to lines of crystal symmetry. In the II Mu, monoclinic uniterminal class of the monoclinic system, there is one plane which is not a plane of crystal symmetry, but is at right angles to a line of crystal symmetry. (See Evans and Davies, "Elementary Crystallography," pp. 9, 13 and chapter xv.)

It follows that only rarely in monoclinic and never in triclinic minerals are the extinctions the same for all colours, but in the orthorhombic class, they either coincide or are very close together, so that there is a sharp extinction even in white light. In monoclinic and triclinic classes they are sometimes very near one another and sometimes wide apart. In the former case there is a fairly exact extinction in white light. In the latter there is no definite extinction in white light, but merely a succession, as the stage is rotated, of obscure dark tints in the neighbourhood of the positions of extinction of the different colours.

Any deviation of optical directions for different colours is known as *dispersion.*

The presence of practically complete extinction is *prima facie* evidence that the mineral is uniaxial, or at least orthorhombic.

14. **Symmetrical Extinctions.**—If the section be at right angles to a plane of crystal symmetry, the extinctions (which will, as we have seen, be the same for all colours) will be symmetrical to the outline of the crystal section. Such an extinction may be termed a *symmetrical extinction.*

V. THE OBJECT IMAGE.

Under this heading I include all observations in which the object itself appears in focus in the field of the microscope. The description of the phenomena observed and the inferences to be drawn from them will involve occasional repetition of statements already made, but this is necessary for the sake of completeness.

1. **Sketch in Zero Position.**—The crystal section is brought into the centre of the field so that it lies beneath the intersection of the cross wires, and the stage is rotated till the index reading is zero. The outline and any other characteristic features should now be traced or sketched, surrounded by a circle representing the margin of the field, and a scale of microns with the numerical value of the magnification added. The scale is constructed with the assistance of an eyepiece micrometer, calibrated by means of the mechanical stage or a stage micrometer in the manner described on p. 5. The position of the cross wires relatively to the crystal when in the zero position is shown by short radial lines drawn inwards from the circumference (Figs. 11 and 12). The right end of the right and left cross wire is marked with 0° outside the circle, because it is the direction of the vibration of the nicol when one only is inserted, and the positions of the other ends of the cross wires by 90°, 180°, and 270°, in the same cyclical order as the graduations on the stage, which are usually contrary to those of the hands of a watch.

2. **Directions inserted on Rotation.**—The stage is now rotated, and as the trace of a face, cleavage, or other rectilineal marking, such as a line (representing a plane)

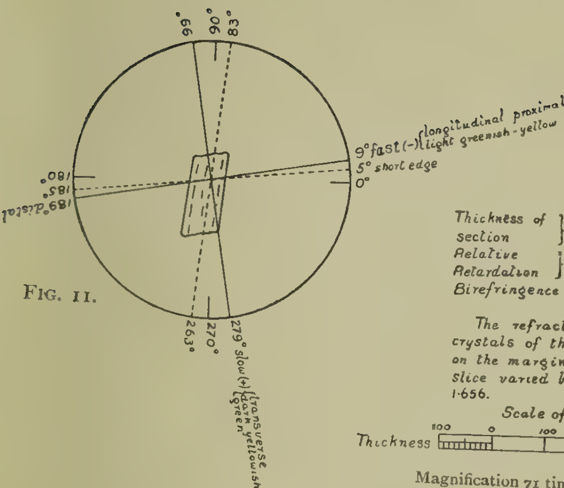

FIG. 11.

Thickness of section } 28 microns
Relative Retardation } 340 micromillimetres
Birefringence 12 millesims or ·012

The refractive indices of crystals of the same mineral on the margin of the rock-slice varied between 1·640 and 1·656.

Scale of microns :-

Thickness 100 0 100 200 300

Magnification 71 times.

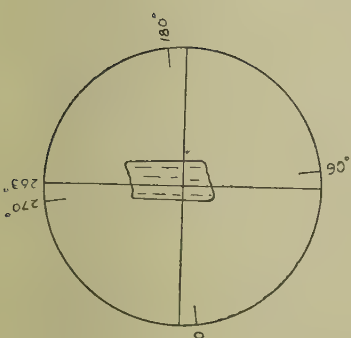

FIG. 12

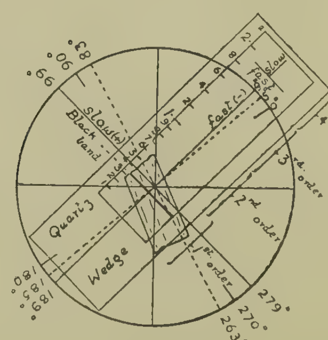

FIG. 13.

PLATE I.

To face p. 46.

of inclusions, comes into a position of parallelism with the right and left cross wire, the latter should be inserted in its new position in the sketch as an interrupted line across the field, and distinguished on its right extremity outside the circle by the index reading of the stage (Figs 11 and 13). As each line comes twice into the right and left position it will have readings at both ends, which will differ by 180°. All these readings will follow each other in the sketch in their cyclical order.

3. **Extinctions.**—Both nicols are now inserted in the crossed position and the stage rotated. If the crystal section remain dark through a complete rotation, the crystal section is either isotropic or cut at right angles to the optic axis of a uniaxial crystal. If it continues uniformly faintly illuminated, it is at right angles to an optic axis of a biaxial crystal. Usually, however, it will be dark at four points in the rotation when the directions of vibration of light traversing the crystal section are parallel to those of the nicols, and therefore to the cross wires. As we have seen, these positions of extinctions are distant 90° from one another.

4. **Exact Determination of the Position of Extinction.**—There is usually some difficulty in determining the position of maximum darkness corresponding to the true position of extinction, even where there is no dispersion, or where monochromatic light is employed. Resort has therefore been had to various methods of obtaining an exact result.

(*a*) One of the simplest of these is to rotate the stage towards the position of extinction alternately from opposite cyclical directions, and to note the readings on each side where the same degree of darkness has been obtained. The mean of several pairs of careful observations will approximate closely to the index reading corresponding to the true position of extinction.

(*b*) In another method which has been investigated in detail by F. E. Wright[1] the crystal is first placed in the approximate position of extinction obtained in the manner already described, and then one of the nicols is rotated through a small but definite angle in either direction, and the degree of illumination that results carefully noted. The nicol is next rotated in the opposite direction through exactly the same angle on the other side of its normal position. If the illumination in the two cases be the same, the supposed position of extinction is correct. If not, the nicol, which has been rotated, is restored to its original position, and the stage is rotated slightly towards the direction in which the darkness was the greater. The same test is then again applied, and, if necessary, the process is repeated till the rotation of one nicol through equal angles in both directions produces the same result.

The angle through which the nicol must be rotated is that which will produce a faint illumination on rotation in one direction at least. It is usually between $\frac{1}{2}$ degree and 2 degrees. It would be convenient if graduations were provided on the mounting of one nicol showing rotations through $\frac{1}{2}$, 1, and $1\frac{1}{2}$ degrees in each direction.

Where the position of extinction is the same for all colours, this method may be applied with either monochromatic or white light, the latter being preferable, not only because the illumination is greater, but also because, when the true position of extinction has not been obtained, the two directions of rotation of a nicol give different interference colours.

(*c*) F. E. Wright has devised a bi-nicol ocular, in which the results of the rotation of *two* upper nicols

[1] *Am. Journ. Sci.*, Series IV., vol. xxvi., pp. 349-368, 379 (1908).

in opposite directions may be observed simultaneously in different parts of the field.[1]

(*d*) A similar effect is obtained by the insertion of right and left handed quartz plates cut at right angles to the optic axis, which rotate the light between the nicols through equal angles in opposite directions in different parts of the field. This is the principle of the Bertrand eyepiece; but in its usual form the plate is so thick—2·5 mm.—that it rotates the light through a large angle—about 60° for sodium light, and greater or less amounts for light with shorter or longer wave length. If it be reduced to a thickness of 40 microns, corresponding to a rotation of 1° for sodium light, much greater accuracy is obtained both with monochromatic and white light in the determination of the position of extinction.[2]

(*e*) Macé de Lépinay introduced the use, in lieu of plates, of right and left handed quartz wedges with their bisecting planes at right angles to the optic axis of the quartz. By the greater or less insertion of this double wedge the desired amounts of equal and opposite rotation may be obtained. Wright's "bi-quartz wedge plate" is an elaboration of the same principle.

(*f*) In all these determinations greater accuracy can be secured by increasing the illumination, but care must be taken that the lower nicol is not injured by overheating (see p. 2).

It is unnecessary to refer here to the other methods which have been introduced at different times for the determination of the exact position of extinction, as few of them are so exact as those which have been described.

5. **Insertion of Directions of Extinction.**—When the stage is in the exact position of extinction—in other

[1] *Loc. cit.*, pp. 374-376, 379.
[2] S. Nakamura, *Centr. f. Min.*, 1905, pp. 267-279.

words, when the directions of vibration in the crystal are parallel to those of the nicols, and therefore to the cross wires—the position of the latter is indicated in the sketch by thick lines traversing the whole field, and the index reading is inserted on the right extremity of the right and left cross wire, while the other terminations of the cross wires are distinguished by the corresponding angular numbers differing from the former by multiples of 90° (see Figs. 11 and 13).

6. **Dispersed Extinctions.**—When there is a distinct difference in the positions of extinction for different colours the direction of extinction for sodium light[1] should be inserted. If the difference be very marked, the directions of extinction for more than one colour may be given.

7. **Parallel Extinction—Angle of Extinction.**—If a direction of extinction is parallel to the length of a crystal section or to a prominent edge or cleavage, it is said to be *parallel* or *straight*. A symmetrical extinction (*ante*, p. 45) is not always a parallel extinction. It may, as in the case of calcite or quartz, in which no prism faces are developed, bisect the angle between the traces of cleavages or faces. In cases where the extinction is not parallel, the angle between the direction of extinction and an edge or cleavage must be carefully measured. The angle will vary among different individuals of the same mineral, but its maximum value, known as the *angle of extinction* of the mineral, is important for its identification. An angle of extinction may be termed fast or slow, according as it is measured with the fast or slow direction of extinction.

In Figs. 12 and 13, the front and back and right and

[1] A bright sodium flame can be obtained by soaking a sheet of asbestos or of paper in a saturated solution of sodium chloride, and, when it has dried, wrapping it round a Bunsen-burner, so that its upper edge is just touched by the flame.

left continuous lines show the positions of the cross wires as seen in the field of the microscope. In Figs. 11 and 13, the directions of extinction are shown by continuous lines across the sketch. In Fig. 11 the stage has been returned to the zero position. In none of these figures is the crystal section actually in the position of extinction.

8. **Pleochroism and Allied Phenomena.**—It follows from what has been stated that light traversing a crystal section of a birefracting mineral consists of two parts vibrating parallel to the two directions of extinction respectively. The light vibrating parallel to these two directions is differently affected by the structure of the crystal. As we have seen, the velocity of transmission of the vibrations parallel to one is greater than that of those parallel to the other, and the index of refraction is consequently less in the case of the former. At the same time the absorption of light may differ considerably both in amount and in the extent to which it affects different colours. For an examination of these differences the crystal is observed with only the lower nicol in place, and the stage is rotated in turn into each of the positions in which a direction of vibration—that is to say, a direction of extinction—is parallel to the right and left cross wire. This, as we have seen (p. 33), will be the direction of vibration of the nicol that is retained, and it will be that of the light which traverses the crystal and meets the eye of the observer. The appearance of the surface of the mineral under these conditions, whether it is rough or smooth, and its luminosity and colour, are observed in each case, and noted in the sketch at the right end of the thick line representing the corresponding direction of vibration.[1]

When the surface of the crystal is distinctly rougher

[1] Fig. 11.

in one position than in the other, it indicates that there is considerably more difference between the refractive index of the light vibrating parallel to the right and left direction and that of the medium in which the section is mounted (Canada balsam or whatever it may be) in the former case than in the latter. This phenomenon is well seen, when Canada balsam is the medium, with calcite and the carbonates isomorphic to it, as well as in the colourless micas. It then causes a characteristic twinkling effect when the lower nicol is rapidly rotated.

9. **The Diagonal Position—Interference Colours and Relative Retardation.**—We now proceed to determine the relative retardation of the section, the nature of which has been already explained (pp. 36-38).

To make this determination the stage is rotated between crossed nicols till the section is extinguished. It is then rotated through 45°, when it will be in the *diagonal position*,[1] and show in most cases *interference colours*. If, as in the case of quartz and most other minerals, the birefringence, and therefore the relative retardation, is practically the same for all the colours of the spectrum, this interference colour will be one of those seen when a quartz wedge is placed in a similar position. Its place in the succession of colours described on pp. 40-43, and hence the relative retardation from which it results, may be approximately determined at sight, unless the relative retardation is so great and the colour so high that it is one of the indistinguishable pinks or greens, or even the white of the higher orders.

[1] See Fig. 13. Here the front and back and right and left lines are the actual cross wires seen when the crystal section is in the diagonal position. They should not be inserted in the *sketch*, which should only show the diagonal lines which were drawn when the crystal section was in a position of extinction, and represent the then position of the cross wires relatively to the crystal section (see p. 46).

Sometimes a doubt may be resolved or a confirmation obtained by repeating the observation with parallel nicols.

There are a few minerals, of which chlorite, idocrase, zoisite, melilite are examples, in which the birefringence and relative retardation vary greatly for different colours, and "anomalous" interference colours which differ from any of those seen in a quartz wedge are the result; but instead of being an unwelcome complication these special colours are of value in giving a ready means of recognizing such exceptional minerals. The dark blackish blue or deep brown seen in many sections of chlorite are, for instance, very characteristic.

In some pleochroic minerals, such as the highly ferriferous tourmalines or biotites, the vibrations in one of the two directions are so strongly absorbed that they can no longer "interfere" with those in the other direction, and in an extreme case no "polarization" or "interference" colours are visible. Indeed, if a quartz wedge be inserted at the same time in the usual diagonal position between the nicols it will have no perceptible effect either in monochromatic or white light, for the light that traverses the crystal section vibrates in one direction only.

Even where there is no pleochroism or difference of absorption between the two directions of vibration, the strong natural colouring of the mineral may so disguise the interference colours that it is difficult to tell their position in the scale of relative retardation, and especially to distinguish the similar tints of different orders.

In any circumstances the higher orders are difficult to distinguish from one another. But in most cases in which the order of the colours is in doubt it is possible to find a point where the margin of the mineral is oblique to the surface of the thin section, forming, in fact, a steep wedge, which shows a succession of bands of

different orders. It is then easy by counting them to determine the order to which the main area of the mineral belongs.

Other methods of determining the relative retardation can only be applied if and when it is ascertained which is the fast and which is the slow direction of vibration in the thin section.

10. **Determination of the Slow and Fast Directions of Vibration, as well as of the Relative Retardation.**—To ascertain the character of the directions of vibration and extinction of a mineral section, that is to say, the directions of the vibrations with the greater and the less velocity of propagation respectively, a birefringent crystal section, the character of whose directions of vibration is known, is placed in the path of the light either above or below the section under investigation, but between the nicols, and the effects of the combination are noted.

(*a*) The accessory most commonly used for the purpose is a quartz wedge with a very low angle between its upper and lower surfaces, which are approximately parallel to the optic axis. For any small portion of its length it does not differ appreciably from a section with parallel surfaces.

The quartz wedge is cut in this country with its length parallel to the optic axis, which is the direction of vibration of the light propagated with the least velocity. The length is therefore slow (+), while the width is fast (–).

A similar wedge may be constructed of gypsum, the surfaces being approximately parallel to the principal (clinopinacoidal) cleavage, and the length parallel to the slow (+) direction. Such a gypsum wedge may be used for all the purposes for which a quartz wedge cut parallel to the optic axis may be employed.

As wedges are sometimes cut in different directions, the character of the length should be engraved on the glass as shown in Fig. 14, and Figs. 15 and 16. Quartz wedges designed for use in Continental microscopes with the slot in a right and left direction are so cut that the directions of vibration make angles of 45° with the length, so that the directions of vibration are diagonal. The

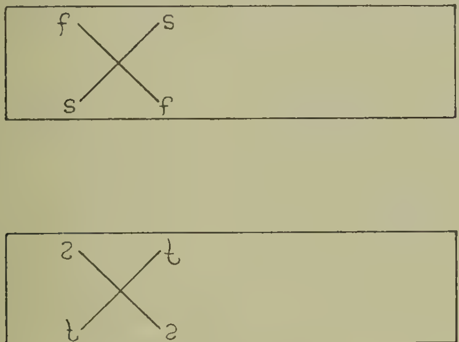

FIG. 14.

slow and fast directions can then be easily interchanged by simply turning the wedge over (Fig. 14).

The wedge should be graduated so as to indicate the relative retardation at different points (see Fig. 15, and Figs. 16 and 17). It should be inserted so as to be in focus (see p. 32), otherwise the colours will be blurred from overlapping and the graduation be invisible.

If the wedge be inserted in the slot between crossed nicols when there is no birefringent mineral in the field, or none which is not in the position of extinction, the normal succession of interference colours is seen commencing at the thin end of the wedge, where, however, the black and darker grey are usually missing on account

of the difficulty already mentioned of preserving the thin end from abrasion.

If, on the other hand, there is a birefringent mineral present in the diagonal position, so that the directions of vibration of the light traversing it are parallel and at right angles to the slot, and therefore parallel to those of light traversing the quartz wedge, the relative retardation of light traversing both the mineral and the wedge will be the combined effect of the relative retardation in each.

If the directions of the slow (+) and fast (–) vibrations respectively in the mineral are the same as those in the quartz wedge, the colour seen at any point where the two are superposed will correspond to a relative retardation equal to the sum of the relative retardations of both. This may be referred to as the *additive* position. As the length of the quartz wedge is slow (+), the direction in the crystal which coincides with that of the slot must evidently in this case also be slow (+). If, on the other hand, the slow direction of the wedge correspond with the fast direction in the crystal section and *vice versa*, the resulting relative retardation will be equal to the difference of relative retardations in the two, and they may be said to be in the *subtractive* position (Fig. 13). In this case the direction in the crystal section parallel to the length of the wedge, and therefore to the slot, will be fast (–). If, then, the relative retardation of the crystal section be within the limits of relative retardation shown by the wedge, there will, as the wedge is advanced through the slot in the subtractive position, be seen a black band traversing the crystal at right angles to the length of the wedge. This marks the point where the relative retardation in the wedge exactly neutralizes that in the crystal section, being equal to it but opposite in character. The relative

retardation of the crystal section itself must therefore be equal to that of the wedge alone at the point where the black band appears, the amount of which is shown by the graduation.

If the mineral gives rise to very high relative retardation, and shows over most of its extent only pale pink and green tints or the white of the higher orders, but on its margin, where it is not so thick, narrow bands of lower order colours, the character of the section may most easily be determined by noticing how these bands move when the wedge is inserted. In they move *inward from* the margin, the mineral and the wedge are in the subtractive position; if *outwards towards* the margin, they are in the additive position.

In such cases it is frequently desirable to employ an especially thick wedge with a comparatively large angle so that the thickness necessary to show the black band may be obtained. It sometimes happens, however, in the case of minerals with high birefringence that, even when the wedge is inserted in the subtractive position and the relative retardation at its thick end exceeds that of the mineral, no definite black band can be recognized; but when the wedge is inserted up to a certain point irregular lines appear, which are too thin for the colours to be recognized, and when the wedge is pushed still farther in they disappear. The mean of the values of the relative retardations of the quartz wedge at the points where it causes these lines to appear and to disappear respectively may be taken to be that of the mineral under examination.

In all cases of difficulty in making this determination it is best to use strictly parallel light, which may be obtained by removing the condenser, or (less completely) by lowering it, or by inserting a diaphragm, or by nearly closing an iris diaphragm.

With strongly pleochroic minerals the black band is not seen, as the excessive absorption of some or all colours in one direction prevents the recombination of the vibrations to form light vibrating parallel to the front and back cross wires. It is, however, generally possible to estimate with a fair amount of accuracy the central position from which the relative retardation with its corresponding colours increases in both directions.

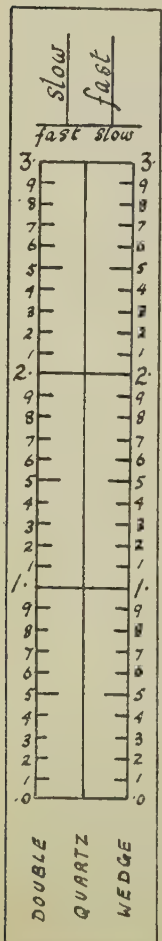

FIG. 15.

Pleochroic sections may be referred to as slow-dark and fast-dark, according as the character of the direction or maximum absorption is slow or fast. The latter case is comparatively rare, and when it occurs, as in ægirine, riebeckite, arfvedsonite, apatite, and andalusite, it is of considerable diagnostic value.

Similarly, where the colour varies considerably, crystal sections may be termed fast-red and slow-green, or as the case may be. Where the contrast is between red on the one hand and blue or green on the other, the fast vibrations are usually associated with the former.

(*b*) *The Double Quartz Wedge* (Fig. 15), which I described in the *Mineralogical Magazine* [vol. xiv., pp. 91-92, 1905], consists of two quartz wedges. One of these has the length parallel to the principal axis, and therefore slow (+), and the width at right angles to that axis, and fast (−). The other has the length at right angles to the principal

axis, and fast, and the width parallel to that axis, and slow.[1] They have the same angle and the same birefringence, so that when cemented by Canada balsam side by side on a glass slip and inserted in the slot between crossed nicols the colours stretch across the two component wedges exactly as if they were one; but if a birefringent crystal section in the field has its directions of vibration parallel and at right angles to the slot, one side will show additive effects and the other subtractive, so that the existence of a small relative retardation is easily recognized, and the amount of the relative retardation may be read off, no matter which direction of vibration in the crystal section is parallel to the slot. It may be noted that the colour in one component wedge opposite the black band in the other corresponds to a relative retardation exactly double that of the crystal section under examination.[2]

All these forms of quartz wedge should be carefully calibrated by means of the dark and light bands seen in monochromatic light of known wave length, such as that of sodium light. The error may thus be determined within ten micromillimetres.

(*c*) *The Gypsum Plate.*—If the relative retardation be small it is difficult to measure, or in some cases even to detect it by a quartz wedge on account of the imperfection of the thin edge of the latter. In such cases it is best investigated by means of a gypsum plate, parallel

[1] In each the median plane bisecting the angle of the wedge is parallel to the principal axis.

[2] This double quartz wedge is quite distinct from that of Macé de Lépinay (p. 49) and from others constructed on a similar principle. The median or bisecting planes of the Macé double wedge are at right angles, not parallel, to the optic axis, and the colours it shows are due to rotation, not retardation. It is only available for determining the exact position of extinction, not for measuring relative retardation. The double wedge described here may be employed for both purposes.

to the clinopinacoidal cleavage, of such a thickness as to show the violet corresponding to a relative retardation of 575 micromillimetres.[1] A very small decrease in the relative retardation is sufficient to modify the colour considerably and cause it to pass into purple or red, while a slight increase changes it to indigo or blue.

The gypsum plate is usually cut with its length parallel to the fast direction.[2] It may be inserted in either slot or in any other place in the course of the light between crossed nicols, but always in a diagonal direction. If a crystal section with low birefringence is now placed on the stage with its directions of vibration parallel and at right angles respectively to this direction, the colour of the plate will be seen to be modified so as to indicate an increase or decrease in the relative retardation. In the former case the vibrations in the crystal parallel to the slot will be fast, in the latter slow.[3]

The relative retardation of the crystal section may then be determined by first determining by means of a quartz wedge that of the combination of a gypsum plate and the crystal section. The stage is then rotated through an angle of 90°, and another determination made. Half the sum of the two relative retardations

[1] Gypsum plates are, however, usually made to show the red of the first or second order, which is not so sensitive to variations in thickness, and therefore easier to produce of a practically uniform tint.

[2] A circular plate mounted in wood is to be avoided, for if it becomes loose, as frequently happens, it loses its correct orientation. Every plate should be marked so as to show the numerical amount of the relative retardation and the character of the length, as in Fig. 14.

It must be remembered that on the Continent gypsum plates, like quartz wedges, are frequently cut with the directions of vibration diagonal to the length (see *ante*, p. 55).

[3] In the case of small minerals with low relative retardation, which are rendered inconspicuous by the bright light to which the gypsum plate gives rise, it is better, if the construction of the microscope permits, to insert the plate in a direction making only a small angle with the cross wire. This diminishes the illumination of the field (F. E. Wright, *Am. Journ. Sci.*, Series IV., vol. xxxv., 1913, p. 66).

will be the relative retardation of the gypsum plate (which should agree with its previously ascertained value) and half the difference, that of the crystal section.[1] If the gypsum plate and quartz wedge are used together, the former should be inserted in the lower slot, leaving the upper for the latter; the upper nicol would then be necessarily placed above the eyepiece.

(*d*) *Combined Quartz Wedge and Gypsum Plate.*—F. E. Wright has devised a useful combination of quartz wedge and gypsum plate,[2] and I have employed the same idea in the following manner (Fig. 16): A quartz wedge is superposed on a gypsum plate showing the sensitive tint, both being constructed with the usual orientation (see above), so

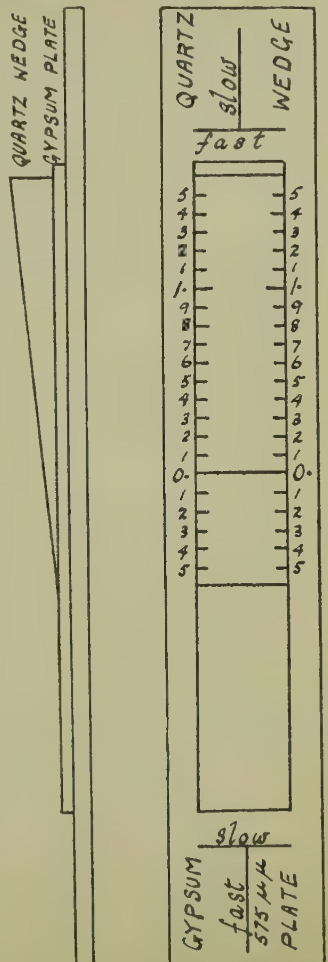

FIG. 16.

[1] This is on the assumption that the relative retardation of the section is obviously less than that of the gypsum plate.

[2] *Journal of Geology*, vol. x., 1902, pp. 33-35. See also *Min. Petr. Mitt.* (Tschermak), vol. xx., 1901, pp. 275, 276.

as to leave beyond the thin end of the wedge a square of gypsum, which may be used as an ordinary gypsum plate. The quartz will show a black band where it exactly neutralizes the gypsum, and the same succession of colours in opposite directions from this point, which is indicated by a line marked zero ; but on account of the imperfection of the wedge stop short a little before the colour of the plate is reached. Every hundred micromillimetres of relative retardation on either side is shown by graduations. If the direction of the crystal section parallel to the slot be fast (–), the black band will move towards the thick end of the wedge; if slow (+), towards the thin end.

(*e*) *Mica Steps* (Fig. 17) consist of a succession of parallel cleavage plates of muscovite, in a direction parallel to the trace of the optic axial plane, and therefore slow. Each should have a relative retardation of 100 micromillimetres. They are of different lengths, and when superposed form a succession of steps each large enough to cover the whole cone of light in the lower slot above the objective, where they are usually employed, though they are equally useful in the focus of the eyepiece, if the upper nicol be placed above them. In either case they show a discontinuous series of colours corresponding to differences of 100 micromillimetres. If they are inserted over a crystal section it is easy to see whether the combination shows additive or subtractive relations. In the former case the stage should be rotated till the fast direction of the crystal section is parallel to the slot. It may then happen that the crystal section is exactly neutralized by one of the steps, so that it is quite dark, and must therefore have the same relative retardation. Usually, however, none of the steps exactly neutralizes the section; but there are two adjoining steps, one of which fails to neutralize the section,

while the other more than neutralizes it, so that neither will be completely dark. If they are equally bright, the relative retardation of the section must be midway between those of the two steps. If one be darker than the other, the relative retardation will be proportionately nearer to that of the darker step. In this way it will be possible to estimate the relative retardation to within 20 or 30 micromillimetres.

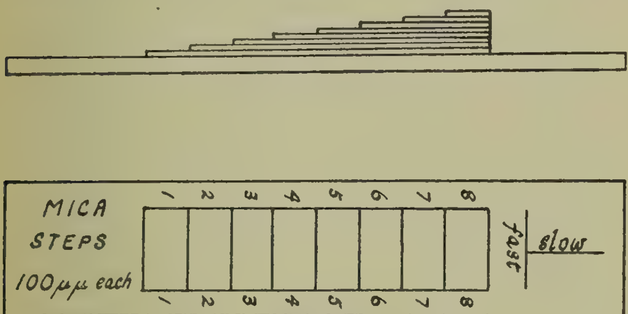

FIG. 17.

If a further approximation be desired, it may be obtained by employing additional smaller mica steps, divided into four portions, with 20, 40, 60 and 80 micromillimetres relative retardation respectively. If the larger mica steps are inserted in the lower slot, the smaller can be placed in the upper. In this way it is possible to determine relative retardation to within 10 micromillimetres and make estimations to within half that amount.

Mica steps are one of the many useful pieces of apparatus devised by Fedorov, but the description given above differs from his directions in some details, having reference chiefly to the amount of the relative retardation represented by each step.

Mica steps may be calibrated by reference to a quartz wedge, the errors of which have already been determined.

11. **Birefringence and Refractive Index.**—In order to obtain the birefringence of the section from the relative retardation it is necessary to determine the thickness. As this will usually involve the movement of the rock slice it is better postponed till after the "directions image" has been examined. For the same reason the determination of the refractive index should also be deferred to a later stage.

12. **Characters of other Directions in the Crystal Plate.**—Any direction in the crystal plate may be considered to have the same fast or slow character as the nearest direction of extinction.

VI. THE DIRECTIONS IMAGE.

1. **The Hodoscope.**—It is frequently desirable to examine simultaneously the optical properties of a number of different directions in a mineral, so that a comprehensive idea of its optical characters may be obtained. For this purpose the microscope is, in the manner which will be described, converted into an optical instrument in which every point in the image corresponds *not* to a *point* in the object under examination, but to a *direction* along which light traverses that object in parallel paths. Such an instrument may be conveniently described as a *hodoscope*, or path viewer—a term which is to be preferred to the word "konoscope" employed by Tschermak. It is, in fact, a wide-angled telescope.

If a microscope, from which the eyepiece had been removed, were directed vertically upwards towards a cloudless sky at night, the images of all the brighter stars within a certain distance of the zenith, dependent on the angular aperture of the objective, would be seen in the principal focal surface of the objective—that is to say, its focal surface for light from an infinite distance. The image of each star would be formed of light which had been travelling by practically parallel paths from it. By day the whole field would be illuminated and every point in it would represent light which had reached the objective from a particular direction. If a crystal section were now interposed close to the objective on the side from which the light was coming, every illuminated point on the focal surface would represent a *direction* in the crystal section, which would be determined by the construction of the

objective, the position of the point relatively to it and the refraction at the surface of the section, which can be allowed for if the refractive index be approximately known. The image thus obtained representing different directions in a crystal may be described as the *directions image*, as opposed to the *object image* in which the microscope is focussed on the object itself.

The majority of optical instruments or apparatus employed for the observation of indices of refraction and other optical constants are in fact hodoscopes or telescopes focussed on infinity, but they differ from the microscope when used to observe the interference figures by having a very much smaller angular aperture.

As it is inconvenient to direct the microscope to the sky, the different directions in the mineral section are illuminated by placing below the stage and above the mirror of the microscope a condenser consisting of a convergent lens or system of lenses. For this reason the directions image is frequently referred to as the "image in convergent light," an altogether misleading expression, since convergent light is habitually employed with high objectives, when the microscope is focussed on the object itself, or, in other words, when the object image is under examination. In observing the directions image it is usually desirable to employ wide-angled objectives, so as to include as great an extent of directions as possible, and the angular aperture of the condenser must be at least as great.

2. **The Bertrand Lens.**—As the directions image formed by the objective is small and somewhat inaccessible, it is usual to observe it by means of a Bertrand lens. This is a convex lens which can be placed, when required, in the tube below the eyepiece, and with the assistance of the collecting lens, forms a secondary directions image in the focus of the eyepiece. The

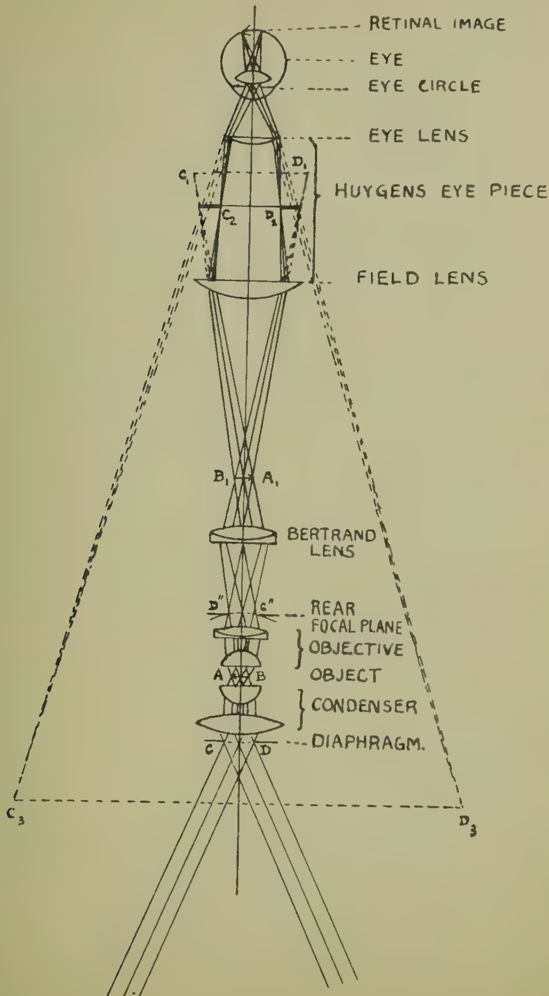
RETINAL IMAGE
EYE
EYE CIRCLE
EYE LENS
D_1
C_1
HUYGENS EYE PIECE
C_2
D_2
FIELD LENS
B_1
A_1
BERTRAND LENS
D''
C''
REAR FOCAL PLANE
OBJECTIVE
A
B
OBJECT
CONDENSER
C
D
DIAPHRAGM.
C_3
D_3

FIG. 18.

Bertrand lens is as a rule inserted a short distance above the objective. It is, however, sometimes placed higher up and then occupies only a small area in the centre of the tube, and thus a large portion of the object image may, if desired, be left visible outside and unaffected by the lens. If this be done, the observer can, without losing sight of the directions image, satisfy himself from time to time as to the point on which the microscope is directed, and may, by moving the object, examine the directions image in one portion of the crystal section after another.

The Bertrand lens should be capable of being focussed by a sliding movement along the axis of the microscope, and it is important that this movement should have sufficient range for the purpose, which is not always the case.

3. **The Becke Lens.**—Instead of inserting the Bertrand lens in the tube, it is possible to obtain the same result more conveniently by placing the Becke lens above the ocular or eyepiece. This is a convex lens or system of lenses, similar to a Ramsden eyepiece, which magnifies the directions image formed in the Ramsden circle of the ocular. It should have a focussing movement.

4. **Isolation of the Directions Image of a Mineral.**—If the mineral under examination is not alone in the field, it is desirable to isolate it, so that the effects of different minerals may not be blended and thus interfere with one another.[1]

(*a*) This object may sometimes be attained by using a small close high-power objective and thus diminishing the extent of the rock slice included in the field.

(*b*) Another method is to cut off all light except that reaching the mineral under examination. For this purpose a diaphragm may be placed a little distance below

[1] J. W. Evans, *Min. Mag.*, vol. xviii., pp. 45-51 (1916).

the condenser which is adjusted so that the image of the aperture in the diaphragm is focussed in the plane of the rock slice.

In some microscopes the iris diaphragm, attached to the condenser for carrying out the Becke method of determining the relative refractive indices of minerals in thin sections (p. 97), may be employed for this purpose.[1] In that case all that is necessary is to focus the microscope on the object, and after nearly closing the diaphragm lower the condenser till the aperture in the diaphragm appears in focus in the rock slice. The glass slip is then adjusted, if necessary, so that the crystal to be observed is in the centre of the field and the diaphragm opened or closed till the maximum area of the crystal, but no portion of any other, is illuminated.[2] It is scarcely necessary to add that the greatest care must be taken to see that the nosepiece is exactly centred so that the crystal under examination and none other appears in the illuminated area during the rotation of the stage. The Bertrand or Becke lens is now placed in position and the directions image can be studied.

(*c*) The same result can be obtained by placing a diaphragm at any point above the object where a real object image is formed, provided of course that such image is not affected by the conversion of the microscope into a hodoscope. One of the following methods may be employed:

(i.) If the eyepiece be removed, an object image can be formed exactly at the upper end of the microscope tube by operating the coarse or fine adjustment. The mineral selected for examination is then brought into the centre of the field, and a cap with a central perforation,

[1] In other instruments the iris diaphragm is so close to the condenser that the latter cannot be lowered sufficiently to bring it into focus. Another diaphragm must then be provided.

[2] Light traversing glass or other isotropic substances will not, however, affect the result if the nicols be crossed.

not larger than the image of the mineral, is placed on the end of the tube. If the eye be now placed close to the aperture, the directions image will be seen low down in the tube in the position already described, illuminated only by light which has traversed the mineral.

(ii.) The eyepiece is retained and the mineral to be studied isolated by means of a diaphragm in the focus of the eyepiece. The Becke lens is then placed in position and the directions image of the mineral, unmixed with other light, is seen. This is by far the most satisfactory procedure, and the microscope should be constructed so as to facilitate its use.

(*d*) The employment of a minute diaphragm immediately below the Bertrand lens rests on no scientific basis, and does not effect clear and complete isolation.

5. **Interference Colours in the Directions Image.**—I now proceed to describe some of the phenomena seen in the directions image, especially those which may be easily observed in minerals in thin sections, and afford important information with regard to the optical characters of the crystal sections, as well as to the directions in which they have been cut.

When the directions image is examined between crossed nicols, it shows in the centre of the field the same interference colour as that seen in the object image. From the centre outwards this passes into other colours corresponding to different amounts of relative retardation which may be greater or less than that in the centre. The colours move with the stage as it rotates without suffering any change of configuration, except that they are liable to extinction in the manner which will now be described:

6. **Isogyrs.**[1]—As the stage is rotated the field is traversed by dark bands, or brushes, which constitute

[1] The "gyr" of isogyr should be pronounced "ghir."

the *isogyr*.[1] The isogyr includes all points corresponding to directions in the crystal followed by light vibrating approximately parallel to the cross wires, and therefore extinguished (see p. 43). As the rotation proceeds, the

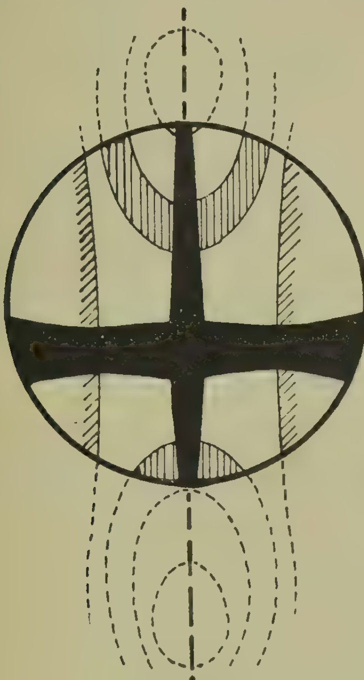

FIG. 19.

isogyr as a rule changes its position and its shape, and from time to time leaves the field altogether (Figs. 19-24).

[1] F. Becke, *Min. Petr. Mitt.* (Tschermak), vol. xxiv. (1905), pp. 1-34; and *Min. Mag.*, vol. xiv. (1907), pp. 276-80; and J. W. Evans, *ibid.*, pp. 230-33.

When the stage is in the position corresponding to extinction in the object image—in other words, when the

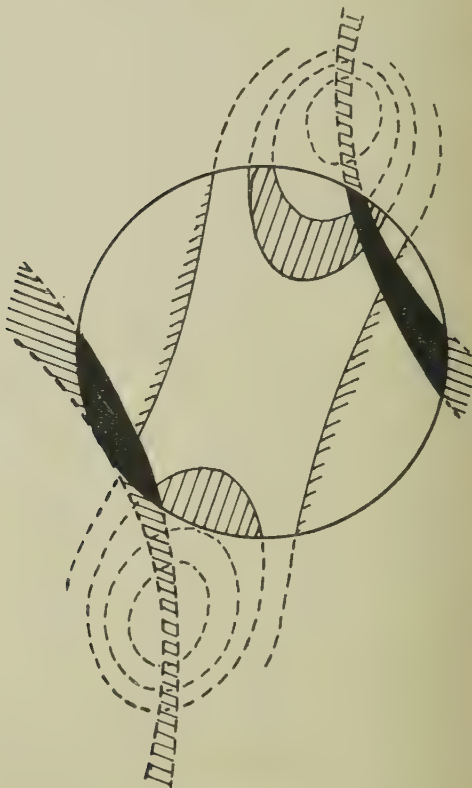

FIG. 20.

vibrations in the plane of the crystal section are parallel to the cross wires—the isogyr passes through the centre

of the field, and is known as a *central isogyr* (Figs. 19 and 22).

The visible portion of the isogyr consists in the majority of cases of a single dark band, which expands towards

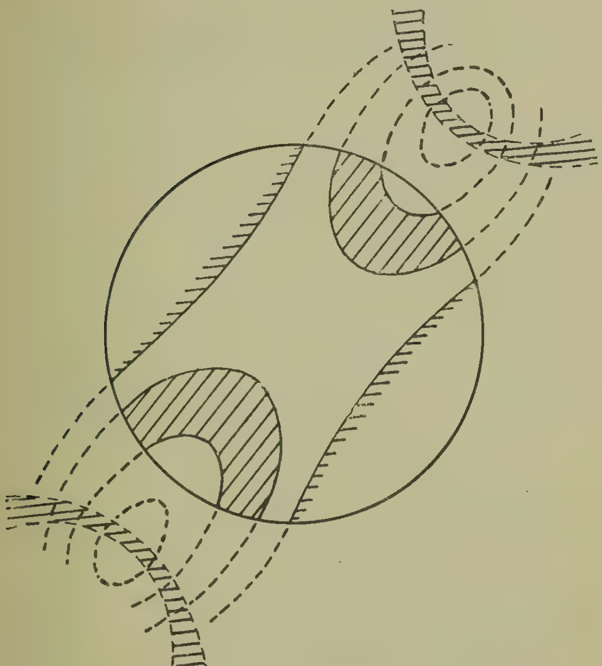

FIG. 21.

the margin of the field to form a less definite brush (Figs. 22-23). A band of this description usually moves four times across the field as the stage rotates, and is then as a rule lost to view (Figs. 22-24).

In other cases the isogyr consists of two dark bands,

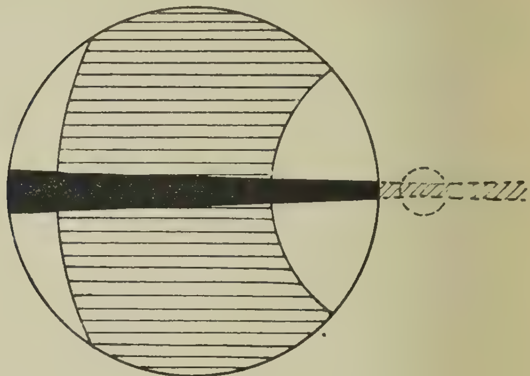

FIG. 22.

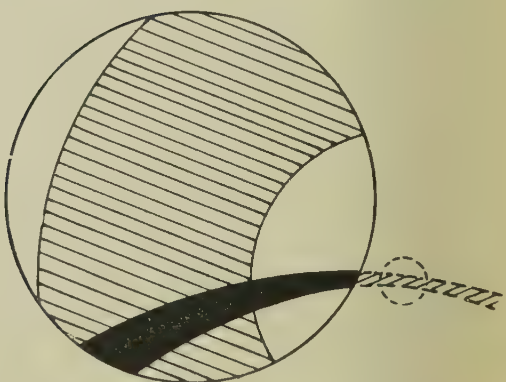

FIG. 23.

which sometimes meet in a cross, and sometimes separate into the two branches of an hyperbola (Figs. 19 and 20).

The following special types of central isogyrs, formed of a single band, may be distinguished :

A *symmetrical* isogyr is straight and parallel to one of the cross wires, and therefore to one of the directions of vibration in the section (Figs. 19 and 22). A section showing a symmetrical isogyr is said to be a *symmetrical section.*

A symmetrical section is always cut at right angles to a plane of optical symmetry, of which the central isogyr is the "trace," or line of intersection with the section.

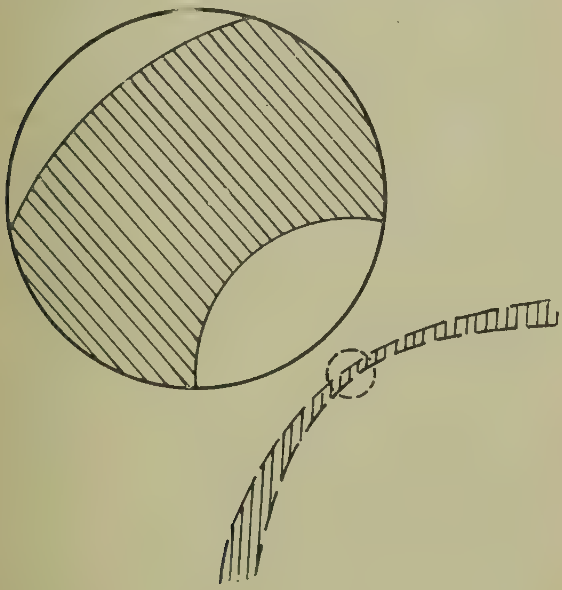

FIG. 24.

Every section of a uniaxial mineral is cut at right angles to a plane of optical symmetry, and is therefore a symmetrical section, while this is only exceptionally the case with sections of biaxial crystals. If, therefore, every

section of a mineral in a rock section shows a symmetrical isogyr, we may safely assume that the mineral is uniaxial.

In biaxial crystals, as a general rule, a central isogyr is curved and oblique to the cross wires (Figs. 23 and 28).

A *pseudosymmetric* isogyr is straight, but is parallel, not to one of the cross wires, but to the line bisecting the angle between them (Fig. 36).

A pseudosymmetric section is only met with in *neutral* crystals—that is to say, those whose optic axial angle is 90°; and the normal of such a section must lie in a plane containing the optic normal and one of the optic axes of the crystal.

If the two bars meet at right angles in the centre and form a cross, each of them will be straight and parallel to the cross wires and therefore symmetrical. The section must accordingly have been cut at right angles to two planes of optical symmetry, and to the line, or axis, of optical symmetry in which they meet. In a *biaxial* crystal this line is either a bisectrix or the optic normal. In the latter case the cross is somewhat indistinct, and in crystals with an optic axial angle approaching a right angle it becomes unrecognizable. If a section of a *uniaxial* crystal show a central cross, it is either cut at right angles to the optic axis, and therefore to an infinite number of planes of optical symmetry, or it is parallel to the optic axis. In the latter case, again, the cross is more or less indistinct, but sometimes quite recognizable.

If an isogyr is formed of two bars, but only one of these passes through the centre of the field, the nature of the isogyr and of the section is considered to be determined by the portion of the isogyr which passes through the centre.

7. **The Movements of Isogyrs.**—The movements of a symmetrical isogyr, when the stage is rotated alternately in opposite directions, are symmetrical to the cross wire to which it is parallel, when it passes through

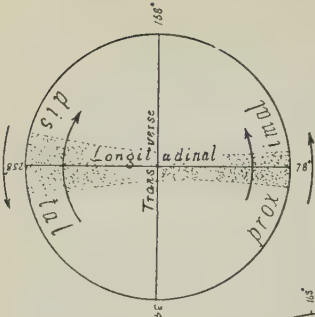

FIG. 25.

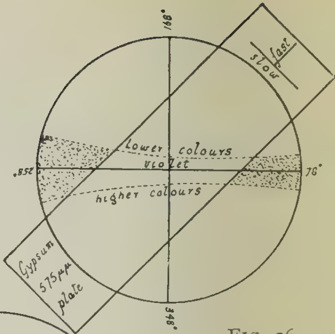

FIG. 26.

FIG. 27.

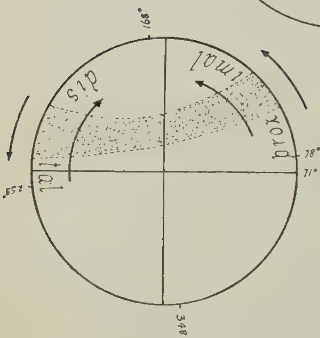

FIG. 28.

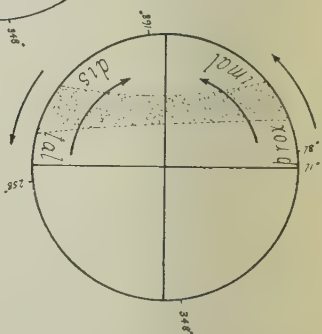

FIG. 29.

PLATE II.

To face p. 77.

the centre of the field; while those of a pseudosymmetric isogyr are symmetrical in the same way to the diagonal to which it is parallel. If the movements are unsymmetrical, the isogyr must be so likewise.

If, when the stage is rotated, one of the ends of an isogyr at the boundary of the field moves round the circumference in the same cyclical direction as that in which the stage is rotated, that end is said to be *proximal*. If it moves round in the opposite direction, or is stationary, it is *distal*. The terms "homodrom" and "antidrom" are used by Becke, but they are misleading if a microscope with rotating nicols be employed, and proximal and distal are accordingly more suited for general use. The manner in which they are applied is illustrated in Figs. 25-36.

In a microscope with rotating nicols the proximal end moves in the cyclical direction opposed to the rotating nicols and the distal end in the same cyclical direction as the nicols.

An isogyr consisting of a single band has usually one end proximal and the other distal. A proximal end is directed towards the nearest optic axis; or, if it be practically equidistant from the two optic axes, to the nearest bisectrix.

An isogyr consisting of two bars intersecting in a cross has in biaxial crystals (Fig. 31) two proximal ends opposite to each other and two distal ends. If the centre of the cross represents a bisectrix, the proximal ends are directed towards the optic axes and the bar to which they belong marks the trace of the optic axial plane. The distal ends lie in the direction of the optic normal. If the section is, on the other hand, cut at right angles to the optic normal, the proximal ends point to the acute bisectrix and the distal towards the obtuse bisectrix. On rotation of the stage the cross breaks up into two hyperbolic branches, each with one proximal and one

distal end. These move away from the centre and may pass entirely out of the field (Figs. 19-21, and Plate III., Figs. 31 and 32).

In sections of uniaxial crystals cut at right angles to the optic axis (Fig. 39) the cross does not break up on the stage being rotated, and the ends are stationary and may be considered distal. The phenomena in sections parallel to the optic axis are similar to those in sections at right angles to the optic normal in biaxial crystals. The proximal ends are directed towards the optic axis, while the bar with distal ends lies in the plane of optical symmetry at right angles to the optic axis.

8. **Pendulum, Parallel, and Fan Movements.**—If the distal end of an isogyr move more rapidly than the proximal end, the movement may be compared to that of a pendulum (Figs. 23 and 27) This happens when the proximal end is directed towards an optic axis. If the section is symmetrical, either it is at right angles to the optic axial plane of a biaxial crystal, or it is a section of a uniaxial crystal, which makes a very large angle with the basal plane, or in other words its normal lies nearly at right angles to the optic axis.

If both ends move at nearly the same rate, the isogyr passes straight across the field, maintaining approximately its rectilinear form and keeping parallel to one of the cross wires (Figs. 25 and 29). This is the case in sections of uniaxial crystals which make only a moderate angle with the basal plane. It is not the only movement occurring in isogyrs of uniaxial minerals, as is commonly supposed to be the case.

If the distal end of an isogyr move less rapidly than the proximal end, the movement is similar to that of a fan (Fig. 28). This is the case in biaxial crystals when the proximal end is directed to a bisectrix. If the section is symmetrical, it is at right angles to

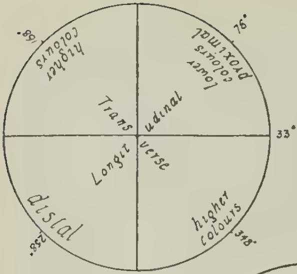

FIG. 30.

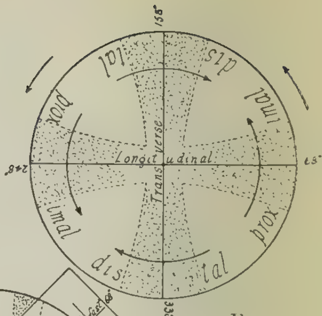

FIG. 31.

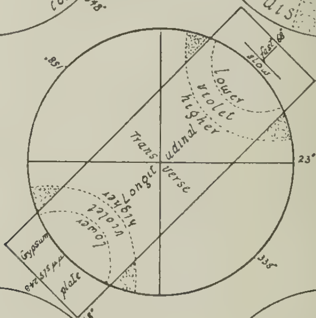

FIG. 32.

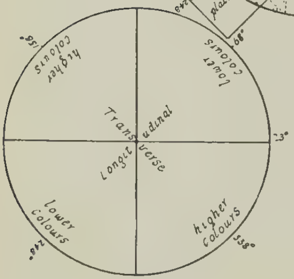

FIG. 33.

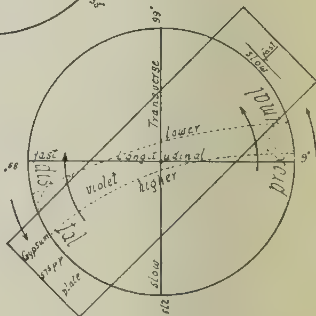

FIG. 34.

PLATE III.

To face p. 79.

one of the planes of optical symmetry passing through the optic normal and a bisectrix—in other words, its normal lies in one of those planes. If it is unsymmetrical, its normal is in the neighbourhood of one of the same planes.

9. **Longitudinal and Transverse Directions.**—A direction of vibration (or, in other words, of extinction) is said to be *longitudinal* when it is parallel to the central isogyr where it passes through the centre, or when it makes an angle of less than 45° with it. The *transverse* direction of vibration is that at right angles to the longitudinal direction. If a central isogyr is *diagonal*, that is to say if it bisects, at the centre, the angle between the cross wires, the directions of vibrations are neither longitudinal nor transverse, but neutral.

The *ends* of a longitudinal direction nearest to the proximal and distal ends of the isogyr may themselves be described as *proximal* and *distal* respectively.

In a central cross which breaks up into hyperbolic branches when the stage is rotated, the horizontal or vertical bar with two proximal ends marks the longitudinal direction, and in the diagonal position this direction becomes the axis of the hyperbola, if one be visible (Figs. 19-21, and Plate III., Figs. 31 and 32).

If there be a central cross which does not break up, the section is, as already stated, cut at right angles to the optic axis of a uniaxial crystal, and all directions are longitudinal (Fig. 39).

10. **The Characters of Isogyrs and Sections.**—The character (fast or slow) of the longitudinal direction (see p. 54) is also attributed to the central isogyr and to the section itself. A diagonal isogyr and its section are said to be *neutral*, for they can be neither fast nor slow, since there is no distinction between longitudinal and transverse directions.

11. **The Determination of the Characters of a Mineral.**—The determination of the character of sections in a rock slice enables us to form a conclusion as to the character of the mineral.

In a uniaxial crystal the character of all sections is the same as the character of the mineral, which is that of its optic axis.

In a biaxial crystal the character of the greater number of sections is the same as that of the mineral, which is that of its acute bisectrix. The smaller the acute optic axial angle the more frequently the character of section coincides with that of the mineral.

A section with pendulum movement and higher relative retardation than most other sections of the same mineral with the same thickness will always have the same character as the mineral itself.

A pseudosymmetric section indicates that the crystal is neutral—in other words, that its optic axial angle is 90° —but only certain sections of a neutral crystal are pseudosymmetric, and neutral sections which are not pseudosymmetric do not necessarily belong to a neutral crystal.

12. **Determination of the Character of the Longitudinal Direction.**—The character of the longitudinal direction is best ascertained in the object image in the manner already described (p. 54), but, as will be seen, it may also be determined from the directions image itself.

To identify the longitudinal direction and its proximal and distal ends in the sketch of the object image, the stage should be rotated till in the directions image the central isogyr is seen to coincide or make an angle of less than 45° with the right and left cross wire and have its proximal end to the right. This may be termed the *index position* of the isogyr, for the index reading will then give the position of the proximal end of the longitudinal direction of vibration.

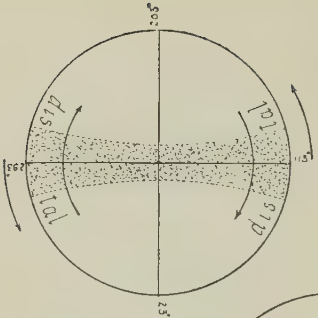

Fig. 35.

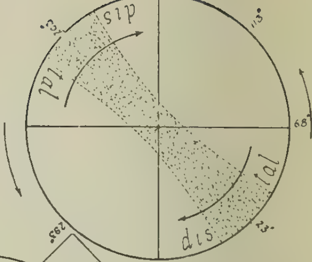

Fig. 36.

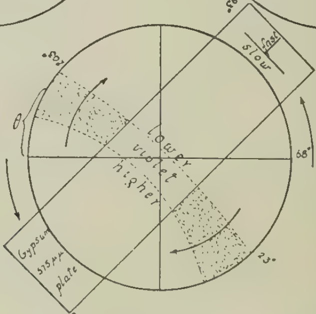

Fig. 37.

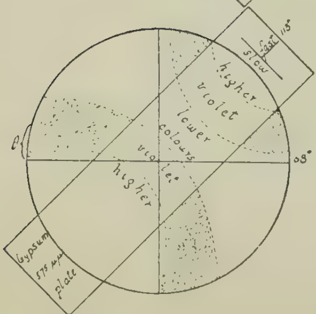

Fig. 38.

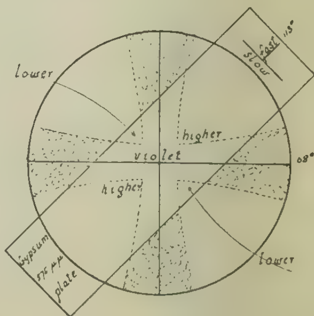

Fig. 39.

PLATE IV.

To face p. 81.

When the isogyr is in the index position, the character of the longitudinal direction may be determined by inserting a gypsum plate in the slot (Figs. 26 and 34) —that is to say, in a diagonal direction. If this be done the isogyr itself will assume the colour characteristic of the plate, but will be bordered by higher colours on one side and lower colours on the other. If the colours are lower on the *same* side as the *proximal* end of the slot, the character of the longitudinal direction and therefore the isogyr and section will be the same as that of the *direction of the gypsum plate parallel to the slot*. If this direction be fast, as it usually is, so also will be the former. By the proximal end of the slot is meant, of course, that nearest the proximal end of the isogyr and of the longitudinal direction of vibration. If the procedure already described has been followed, this will be the right-hand end. If the colours are higher on the same side as the proximal end of the slot, the character of the section will be opposite to that of the direction in the gypsum plate parallel to the slot. If the latter be fast, the former will be slow.

For instance, if the slot be in the position indicated in Figs. 26 and 34, and the colours be lower on the margin of the isogyr farther from the observer as in those figures, the character of the section will be the same as that of the gypsum plate parallel to the slot. If, then, the length of the gypsum plate be fast, the section will be so likewise.

These methods apply both to uniaxial and biaxial crystals. The inferences that can be drawn as to the character of the mineral from the characters of one or more sections have already been described (pp. 79 80).

When a microscope with rotating nicols is employed, the longitudinal direction remains unaltered in position, and it can be recognized at once from the course of the

central isogyr, and the character of the section can be determined by the method just described.

13. **Sections Perpendicular to an Optic Axis.**—These may be recognized in the object image by the darkness in all positions[1] in a uniaxial mineral, and in a biaxial mineral by a feeble illumination which does not vary when the stage is rotated. They show no relative retardation, and are therefore apparently, but not really, isotropic.

If a gypsum plate be inserted in the slot over the directions image of such a section of a uniaxial crystal, the black cross in the directions image will be represented by a cross of the colour characeristic of the plate; and if the mineral be of the same character as the direction in the plate parallel to the slot, the quadrants through which the slot passes will show higher colours, and the other quadrants lower colours, while if it be of the opposite character, the contrary will be the case. If a quartz wedge or mica ladder possessing the same character as the mineral be pushed in progressively, the rings of colour in the former quadrants will contract, and in the latter will expand. If it possess the opposite character, the same phenomena will occur in the alternate quadrants.

In biaxial crystals cut at right angles to an optic axis, the isogyr always passes through the centre, and has two distal ends. In certain positions it is straight and parallel to a cross wire and lies in the optic axial plane. If then the stage is rotated through 45° towards the slot, the isogyr becomes a branch of an hyperbola with its axis parallel to the slot (Fig. 37). If a gypsum

[1] Isotropic crystals will also be dark in all positions in the object image, but the directions image will show a uniformly dark field instead of a cross, unless, as sometimes happens, the glass of the objective is in a state of strain, when a feeble uniaxial cross may be visible.

plate be now inserted, the hyperbolic isogyr will show the interference colour of the plate, and at the same time, if the crystal have the same character as the direction in the plate parallel to the slot, the concave margin will exhibit higher colours (Fig. 37), while the convex margin will exhibit lower colours. If the crystal have the opposite character, the reverse will be the case.

14. **Estimation of the Optic Axial Angle.**—The amount of curvature of the isogyr in this position gives some idea of the magnitude of the acute optic axial angle. If the isogyr be straight, the angle will be 90° (Fig. 36), while if it forms a right angle coinciding with two arms of the cross wires, it is 0°. In this case the other branch of the hyperbola coalesces with it, forming the constant cross characteristic of a uniaxial crystal (Fig. 39).

A very rough approximation to the optic axial angle, which may be employed for determinative purposes, is obtained by taking the angular distance θ round the circumference of the field between the darkest point in one end of a branch of the hyperbola and the nearest cross wire, and doubling it (Fig. 37). The result is usually too high, especially for medium angles, in which the error may amount to 10°. F. Becke[1] has shown how a much more accurate result may be obtained, and a still more rigorous procedure is described by F. E. Wright.[2]

These methods may be applied even when the section is not exactly at right angles to the optic axis, if the point of emergence of the latter appears in the directions image (Fig. 38). Such sections may be recognized

[1] *Min. Petr. Mitt.*, vol. xxiv., pp. 35-44, 1905; *Min. Mag.*, vol. xiv., p. 280, 1907.

[2] *American Journal of Science*, Series IV., vol. xxiv., pp. 332-341, 1907. In the same paper other methods are discussed.

in the object image by the comparatively low relative retardation.

15. **Sections showing a Central Black Cross, which breaks up on Rotation of the Stage.**—Such a section may be parallel to the optic axis of a uniaxial crystal or at right angles to one of the axes of optical symmetry in a biaxial crystal, whether it be an acute or obtuse bisectrix or an optic normal. Unless it be at right angles to an acute bisectrix, the character of the longitudinal direction of vibration (see p. 80) will be that of the crystal, and this will always be the case if the section show high relative retardation compared with most other sections of the same mineral with the same thickness. The black crosses seen in sections of uniaxial crystals parallel to the optic axis, and of biaxial crystals at right angles to the optic normal are distinguished by the rapidity with which they break up and leave the field when the stage is rotated. Where the optic axial angle is small, sections at right angles to the obtuse bisectrix resemble those at right angles to the optic normal.

In neutral crystals and in those in which the optic axial angle differs but slightly from a right angle, the optic normal, as we have seen, shows no cross, and those seen in sections at right angles to the two bisectrices are indistinguishable from one another in the manner in which they break up on rotation.

If the optic axial angle is so small that both optic axes are visible in the same section, the methods already described for the case where one optic axis is present may be employed (Fig. 32).

16. **Variations of Relative Retardation in a Directions Image.**—There is usually a decrease in the relative retardation indicated by the interference colours towards the *proximal* margin or margins of the field, and this may

be utilized to determine the position of the longitudinal direction and its proximal end. For this purpose the stage is rotated through 45° from the position of extinction (when the isogyr passes through the centre, see p. 79). Unless an optic axis is visible, the isogyr will then have passed out of the field and the region of lowest interference colours will mark the position of the proximal end of the longitudinal direction (Fig. 30). If the section be at right angles to an axis of optical symmetry, there will be two opposite regions of lowest relative retardation (Fig. 33), and the line joining them will be the longitudinal direction. This method is frequently useful where the isogyr is indistinct.[1]

In doubtful cases the gypsum plate may be inserted, and then the region that approximates most closely to the colour of the plate will have the lowest birefringence and indicate the proximal end and longitudinal direction. If this be at a point within 45° of the slot and the colour be higher than that of the gypsum plate, the character of the section will be the same as the character of the length of the gypsum plate. If it be more than 45° from the slot, *or* the colour be lower, the character will be opposite to that of the plate. If *both* these conditions hold good, it will be the same as that of the length of the plate. In neutral sections the lowest colour will be about 45° from the slot.

If the optic axis be in the field, the line joining it to the centre will be the longitudinal direction. Some portions of the field will then have a higher and others a lower colour than the gypsum plate, and the colour in the centre of the field will determine the character of the section, unless of course the optic axis is in the centre of the field, when the character of the section will be undefined by this method.

[1] J. W. Evans, *Min. Mag.*, vol. xiv., pp. 233-4, 1907.

17. **Theodolite Stage.**—In recent years Fedorov has introduced the "universal" or *theodolite stage*, by means of which the properties of light vibrating in different directions may be studied in parallel light in the object image of a single section by rotating the latter on two or more axes. The subject is, however, too extensive to be considered on this occasion.

VII. DISPERSION IN THE DIRECTIONS IMAGE.

1. **Uniaxial Crystals.**—In uniaxial crystals the optic axis and isogyrs are the same for all colours and there is no dispersion of the phenomena in the directions image.

2. **Biaxial Crystals, General Principles.**—In the orthorhombic system the lines of optical symmetry, the bisectrices and optic normal are the same for all colours, and this is also true for the planes of optical symmetry. The only dispersion is due to the variation in the magnitude of the optic axial angle for different colours and consequently of the position of the optic axes and of the directions of extinction and isogyrs.

In the monoclinic system, one line of optical symmetry, either a bisectrix or the optic normal, and the plane of optical symmetry at right angles to it are the same for all colours; but the other lines and planes of optical symmetry, the optic axial angles, and the positions of the optic axes, vary with the colour and give rise to dispersion phenomena in the directions image.

In the triclinic system all the optical relations are dependent on the colour and give rise to dispersion by their variation.

It is impossible to describe here in detail all the results of the dispersion of isogyrs and optic axes. It will be sufficient to indicate the phenomena seen in sections cut at right angles to bisectrices or, where the bisectrices are themselves dispersed, at right angles to their mean position.

It will then be possible to interpret by analogy the phenomena seen in sections cut in other directions. The

most important of these are sections cut approximately at right angles to optic axes. The phenomena in that case are essentially the same as those shown by an optic axis when it is in the margin of the field of a section at right angles to a bisectrix.

Where dispersion is well marked it becomes of diagnostic value, and its characters in individual minerals will be described in the second part of this book.

3. **Isogyrs.**—In all biaxial crystals the position of the isogyr varies with the colour unless the section be cut

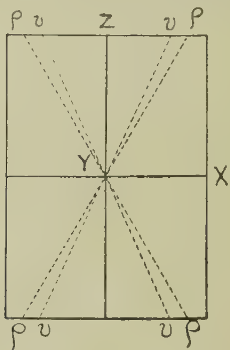

FIG. 40.

at right angles to a plane (or two planes) of crystal symmetry, which is (or are) parallel to one (or both) of the cross wires. The isogyr will then, as we have seen, form a line (or two lines at right angles) parallel to the cross wire (or cross wires).

In other cases the position of the isogyr will shift with the colour, so that points in the directions image included in the isogyrs for some colours may not be included in those of others. If white light be employed the latter colours only will appear at such a point, the former being obliterated. As a rule, however, the isogyrs for

different colours overlap sufficiently for the centre of the combined isogyr to be dark, while the opposite margins show complementary colours which will occupy positions the reverse of the dark isogyrs seen in monochromatic light of corresponding colours.

With parallel nicols the isogyrs will be white and the marginal colours will correspond directly in position to the character of the dispersion.

4. **Dispersion in Orthorhombic Crystals.**—In the orthorhombic system the dispersion in the directions image is simply the result of the variation of the optic axial angle with the colour. If the acute optic axial

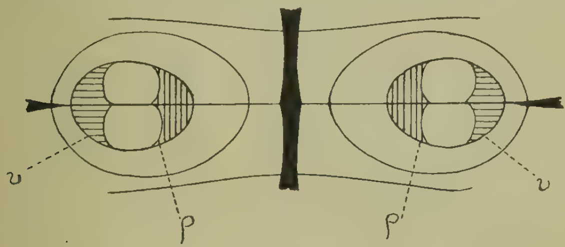

FIG. 41.

angle 2V is larger for red light than for light towards the violet end of the spectrum, the fact is expressed by the inequality $V\rho > Vv$[1] or more briefly $\rho > v$ (see Fig. 40); the contrary state of things by $V\rho < Vv$ or $\rho < v$.

In the former case the acute optic axial angle will open wider, if the colour changes from violet to red; in the latter it will become smaller.

The effect of the dispersion on the interference figures is well seen in the sections cut at right angles to the acute bisectrix. These show a symmetrical arrangement about the centre and about the traces of the planes of

[1] $V\rho > Vv$ may be read "V rho greater than V upsilon," or "V red greater than V violet."

optical symmetry (the optic axial plane and that at right angles to it) whether the traces of the planes be parallel to the cross wires (Fig. 41) or make an angle of 45° with them (Fig. 42) in the diagonal position.

If $V\rho$ be greater than Vv, the "eyes," or the points of emergence of the optic axes, for red light will be further

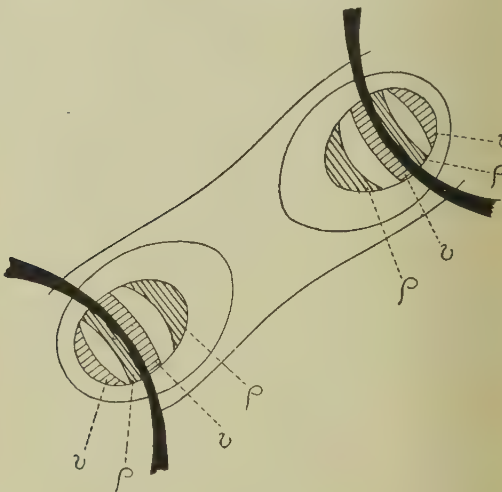

Fig. 42.

apart than those for blue and violet light (Fig. 43). Accordingly if white light be employed, and the traces of the two planes of symmetry at right angles to the section be parallel to the cross wires (Fig. 41), the outer part of each "eye" will be *red* and the inner blue or violet. In the diagonal position, when the section has been rotated through 45°, the "eyes" will coincide with the apices of the hyperbolic isogyr. These will be further apart for red than for violet light (Fig. 42). Consequently red

will be absent on the outer, *concave*, margin of each apex, which will therefore be illuminated mainly by blue and violet light, whereas on the inner, *convex*, side red will appear (Fig. 42).

In a few exceptional cases the acute bisectrix for one colour is the obtuse bisectrix for another, or a bisectrix

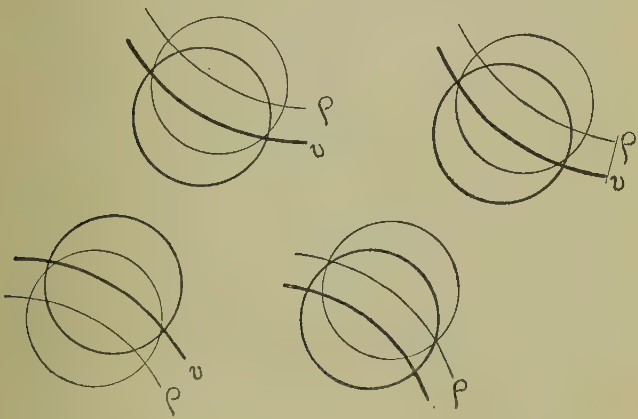

FIG. 43. FIG. 44.

and the optic normal may change places for different colours, as is the case with brookite. In such cases anomalous interference phenomena result.

The dispersion of orthorhombic crystals is also well seen in sections at right angles to an optic axis where, as we have seen, the isogyr, except in neutral crystals, in the diagonal position is curved with the convex side towards the direction of the acute bisectrix. If then ρ is greater than υ, the convex side will be edged with red and the concave side with blue and violet as before.

The dispersion characteristic of orthorhombic crystals

may be termed *angular*, as it depends on variations in the optic axial angle. It is also described as *rhombic* or

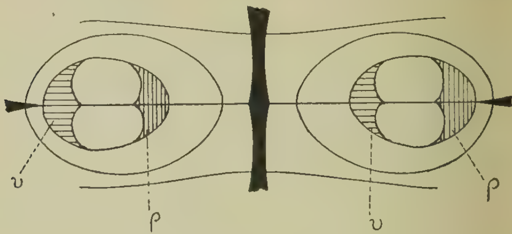

FIG. 45.

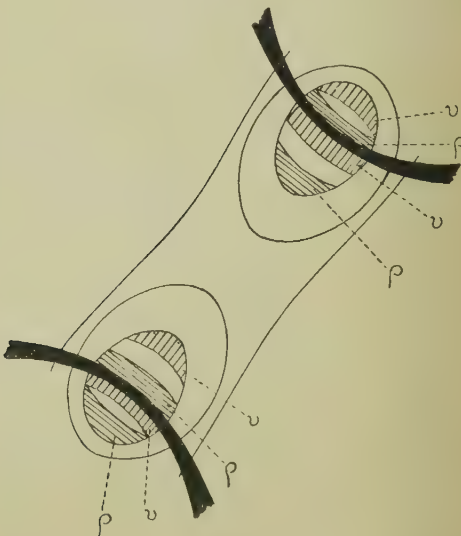

FIG. 46.

orthorhombic, though it may occur in the monoclinic and triclinic systems in addition to the types of dispersion peculiar to these latter.

5. **Dispersion in Monoclinic Crystals.**—In monoclinic minerals angular dispersion is combined with other kinds of dispersion, due to the fact that only one of the three axes of optical symmetry coincides with an axis

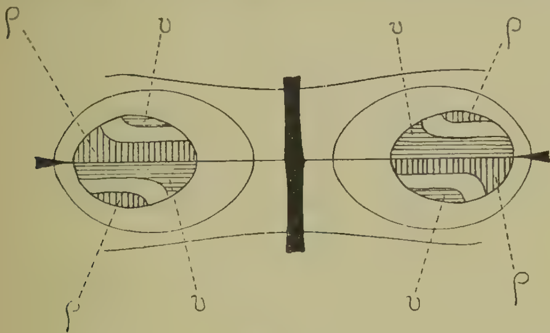

FIG. 47.

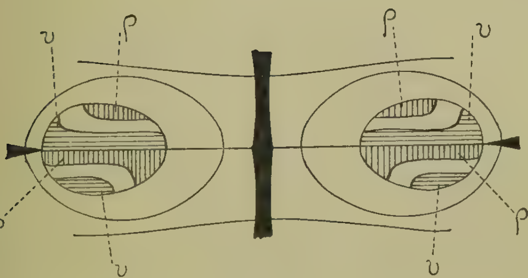

FIG. 48.

of crystalline symmetry—the ortho-axis—and is therefore fixed.

(*a*) If this fixed axis of optical symmetry is the optic normal (Figs. 44-46), the optic axial plane, containing the two bisectrices and two optic axes, will coincide with the clinopinakoid ($O\epsilon^1 O$), the plane of crystallographic sym-

metry.[1] This plane is the same for all colours, but for different colours not only will the angle between the optic axes vary, but also the positions of the bisectrices in the optic axial plane.

Consequently as the colours vary the eyes are shifted laterally along the line joining them, which is the trace of the optic axial plane (see Figs. 44 and 46). The resulting figures in white light will therefore be symmetrical to this line, but not to any line at right angles to it (see Figs. 45 and 46).

This kind of dispersion has been termed *inclined*, because the bisectrices and optic axes are differently inclined to the vertical axis for different colours. *Lateral* dispersion would be a better term.

(*b*) In other cases one of the two bisectrices coincides with the ortho-axis and the other, as well as the optic normal, lies in the plane at right angles to it (Figs. 47 and 48).

A section at right angles to the former position shows the eyes for different colours rotated through a small angle about the bisectrix, and the interference figure is symmetrical about the centre (Fig. 47). Its dispersion is described as *crossed* or better *rotated* (Fig. 47).

In a section cut at right angles to the other bisectrix the "eyes" of the optic axes move, as the colour changes, in a direction at right angles to the line joining them (the trace of the optic axial plane), so that their positions for different colours are parallel. The interference figure in white light is therefore symmetrical to a line at right angles to the line joining the eyes (Figs. 48 and 49). This is known as *horizontal* dispersion, though *parallel* dispersion would be more descriptive of what is actually seen.

[1] Except in the uniterminal (II Mu) class, which has no plane of crystallographic symmetry.

The *crystal* is said to have rotated (crossed) or parallel (horizontal) dispersion according as the dispersion shown by the *acute* bisectrix is rotated or parallel.

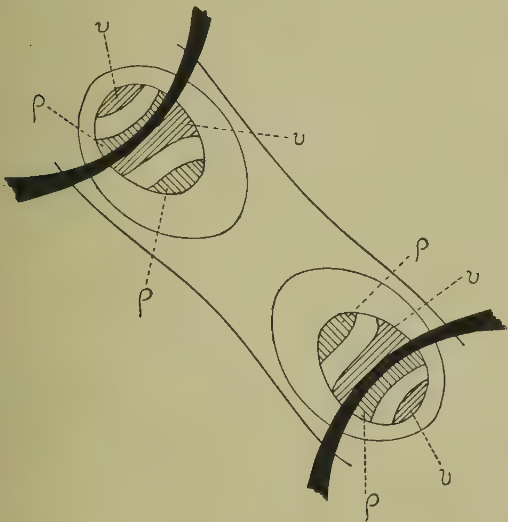

FIG. 49.

6. **Interference in Triclinic Crystals.**—Triclinic crystals show irregular dispersions, which are allied to one or more of the orthorhombic and monoclinic dispersions, but are never symmetrical either to a line or a point.

VIII. OTHER DETERMINATIONS.

1. **The Thickness of the Rock Slice.**—The only practicable method of determining the thickness of an ordinary rock slice is to select a known mineral whose maximum birefringence is known and not too low, such, for instance, as quartz, orthoclase, olivine, calcite, and (for approximate results) an acid or intermediate plagioclase. Search is then made for the section of this mineral which shows the highest relative retardation, and it may be assumed that its birefringence has as nearly as possible the maximum value. Suppose the mineral to be quartz, with a birefringence of 9 millesims (0·009), and the greatest relative retardation observed to be 315 micromillimetres. Then the thickness of the section will be $315 \div 9 = 35$ microns.

The thickness should be determined, if possible, at several points so as to obtain an idea of its variation in different parts of the rock slice. If the thickness of the rock slice is not uniform, that of the crystal section must be estimated approximately from its position in the slice. The thickness should be stated on the sketch, and indicated by the depth of the scale (Plate I., Fig. 11), expressed in the same units as the length. If the thickness is not uniform, the amount of variation may be indicated in the same way.

2. **The Birefringence.**—Knowing the thickness of a crystal section and its relative retardation, we are able to determine its birefringence by dividing the latter by the former. For instance, if the section has a relative retardation of 340 micromillimetres and a thickness of

28 microns, the birefringence will amount to $340 \div 28 = 12$ millesims or 0·012.

A number of different crystals of the same mineral are dealt with in this manner, and it may be assumed that the maximum birefringence thus obtained falls but little short of the maximum birefringence of the mineral.

3. **The Refractive Index: Becke Method.**—A knowledge of the index of refraction of a mineral is a valuable means of recognition. In the case of a thin section in a rock slice only relative determinations of refractive indices are possible in an ordinary petrological microscope, comparison being made with the Canada balsam or other medium in which the rock slice is immersed, or with another crystal with which it is in contact.

For the Becke method a high power is employed, and the cone of illumination is narrowed. This may be effected by removing or lowering the condenser and inserting a cardboard slip with a hole one or two millimetres in diameter ten or twenty millimetres below the stage.[1] A slit of the same diameter placed in the same position parallel to the boundary between the section of the crystal and the medium or adjoining crystal may be substituted. This is equally effective and does not cut down the light to the same extent.[2] The boundary surface must be at right angles, or nearly so, to the surface of the rock slice. This can be verified by observing if it remains constant in position when the focus is varied.

If now there be an appreciable difference between the refractive indices on opposite sides of the boundary, one margin of the boundary will usually be seen to be lighter than the field in general and the other darker. If the

[1] An iris diaphragm is often provided for this purpose, and is more convenient.

[2] J. W. Evans, *Min. Mag.*, vol. xviii., pp. 120-2, 1916.

objective be focussed on a point in the neighbourhood of the upper surface of the section, the light margin of the boundary will be on the side with the higher refractive index and the dark margin on that with the lower refractive index. If the focus be sufficiently lowered, these bands will be reversed in position.

In this way it is possible to determine whether the

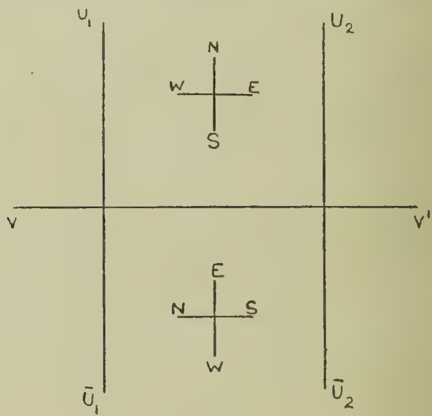

FIG. 50.

refractive index of a crystal mounted in Canada balsam is higher or lower than that of this substance. If, however, the crystal is uncovered, and its margin free from balsam, it may be immersed in a succession of films of liquid of different refractive indices and its refractive index thus determined between comparatively narrow limits.

If the crystal section be birefringent the observation should be made with the lower nicol in position, and first one and then the other direction of vibration in the crystal should be brought into parallelism with the

direction of vibration in the lower nicol. In this way the indices of refraction parallel to both directions of vibration may be determined.

If the directions of vibration of adjoining crystal sections are parallel, exact comparison of the refractive

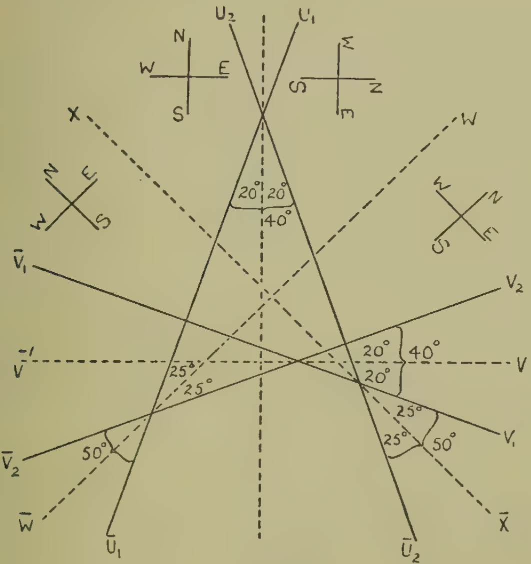

FIG. 51.

indices corresponding to each pair of parallel directions may be carried out in the same manner (see Fig. 50). In other cases *parallel* nicols should be employed and the stage rotated till their direction of vibration bisects the angle between the directions of the pairs of vibration the refractive indices of which are to be compared (see Fig. 51). In all cases a comparison of the *mean* refractive indices may be made by dispensing with the use of a nicol.

IX. SUMMARY OF PROCEDURE.

All the particulars obtained in the investigation of the mineral sections should be embodied in the sketch as shown in Plate I., Figs. 11-13.

The following is a brief abstract of the procedure in the detailed examination of the optical characters of a mineral.

A. Examination of the object image.

1. With stage in zero position, sketch the mineral and indicate the positions of 0°, 90°, 180°, and 270° by short lines directed inwards from the circumference (p. 46).

2. Determine the positions of edges, cleavages, and other rectilinear directions in the mineral and indicate them by discontinuous lines through the centre, each distinguished by its two index readings on opposite sides of the field (p. 46).

3. Determine the positions of extinction (directions of vibration) and show them as continuous lines through the centre with index readings on the margin (pp. 47-50).

4. Note the absorption colours and other phenomena shown by light vibrating in these directions (p. 51).

5. Determine the character of the directions of vibration and the amount of relative retardation (pp. 52-54).

B. Examination of the directions image.

6. Determine the longitudinal direction and its proximal end, and deduce the character of the section, noting at the same time the nature of the movement of the isogyr and any special features in the directions image (pp. 79-86).

All the above observations should be made, if possible, without moving the object. If any movement be

necessary, it should be made without changing the orientation. This is best effected by the use of a mechanical stage.

C. Observations extending to other crystals of the same mineral and other minerals.

7. Determine the thickness of the rock slice and calculate the birefringence of the mineral under examination (p. 96).

8. Study the interference figures of other sections of the same mineral, especially those cut in special directions (pp. 82-85).

9. Determine the character or sign of the mineral (p. 54).

10. Determine the refractive index of the mineral as far as circumstances permit (pp. 97-99).

X. MINUTE CRYSTALS, GRAINS, AND FRAGMENTS OF MINERALS.

1. **General Principles.**—These objects can be studied on lines similar to those already described for mineral sections in thin rock slices. Rocks may be broken up into powder for this purpose, and it is, then, very desirable to obtain good cleavage plates among the fragments produced, for these are parallel to definite directions and furnish exceptionally precise information. With this in view the rock should be crushed in a steel mortar by direct vertical blows and not ground down by lateral or rotary movements. After each blow the fine material should be sifted so as to save it from destruction by further blows. The coarseness of the fragments required depends on the grain of the rock. They should be sufficiently small to be transparent at least in part and to consist in the majority of cases of only one mineral.

2. **Immersion.**—Under the petrological microscope the optical phenomena of crystals, grains or fragments are distorted to a greater extent and in a more irregular manner by the refraction at the surface of the object than in the case of a thin section. It is therefore highly desirable to have them immersed in a liquid with as nearly as possible the same index of refraction. In studying the object image (see p. 46) it is necessary to concentrate the attention on one point at a time—for instance, the highest point of the object.

3. **Relative Retardation and Birefringence.**—The relative retardation and birefringence are determined in the manner already described. It is usually very easy to

recognize the order of the colour shown there, as the colours can be followed in succession from the margin. Again, the directions of fast and slow vibrations can be recognized with facility by means of the quartz wedge, because in the subtractive position the colours move inwards from the margin as the wedge is advanced and in the additive position in the contrary direction.

In order to determine the birefringence it is necessary to ascertain the thickness of the mineral or crystal at the point selected. This may usually be determined by the graduated fine adjustment for focussing. The point selected on the upper surface of the object is first focussed and then similarly a scratch on the upper surface of the glass slip supporting the object or a fine speck resting on that surface. The difference of the two readings measured in microns is multiplied by the refractive index of the medium in which the object is immersed. Sufficient accurate results are sometimes obtained especially in the case of isotropic minerals, by focussing the glass, or lower surface of the mineral, through the mineral and multiplying it by the refractive index of the mineral determined as described below, or merely estimated from its appearance or supposed nature.

In this manner determination of the birefringence corresponding to a section of the indicatrix parallel to the stage of the microscope may be obtained sufficiently accurately to enable the mineral to be identified.

4. **Directions Image.**—In the directions image the isogyrs are as a rule well seen and but little modified by the refraction at the surface, so that the methods of interpreting them which have been described may be freely applied.

The distribution of the interference colours in the field of the directions image is, however, usually seriously affected and no reliance can be placed upon it.

5. **Index of Refraction.**—(*a*) If a crystal or grain be immersed in Canada balsam or other medium, such as a highly refracting liquid or a larger crystal, the relation between its refractive index and that of the surrounding material is best determined by the Schröder van der Kolk or "shadow" method. A condenser is employed, but it must be placed *close* below the object, or the effects will be reversed. One side of the illumination is then shaded, usually by the finger placed below the lower nicol. If a shadow appear on the same side of the object as the finger is placed, the refractive index of the object is higher than that of the medium. If it appear on the opposite side, the refractive index is lower than that of the medium. By inserting a nicol and varying its position, the two directions of vibration can be separately examined in the manner already explained.

With monochromatic light this method gives good results. It is usual to provide a series of liquids, the refractive indices of which differ by small amounts, starting from about 1·47 and extending up to 1·76, the refractive index of methylene iodine, or 1·83, that of a solution of sulphur in methylene iodide, which is, however, not so satisfactory. If an exact determination be required, a mixture of two liquids is prepared, which has as nearly as possible the same refractive index as the mineral, and the index of refraction of this mixture is determined by the Abbé refractometer. It is important to remember that the refractive indices of liquids change considerably with temperature.

If white light be employed, the phenomena are complicated by the fact that the dispersion of the colours in liquids is usually much greater than with solids of the same refractive index, and a series of colour phenomena may result, which complicates the observation. In the case of minerals with decidedly higher or lower refractive

indices than the medium there is no difficulty; but if the mineral has about the *same* refractive index for *blue* light as the medium, but a higher refractive index for *red* light, only the red light will be obscured on the same side as the finger, so that the shadow will be on that side, but will be illuminated by a bluish tinge. When *all* the refractive indices of the mineral are included between the extreme indices of the medium, there will be a bluish colour on the finger side, and a yellowish-red one on the opposite side; and when the *red* refractive indices are the *same* but the *blue* refractive index of the medium is greater, there will be a red shadow on the far side. The colours obtained with particular liquids are sometimes characteristic of particular minerals, and may thus be employed for their identification.

(*b*) The method of determining the refractive index by means of focussing (Duc de Chauluc's method) gives approximate results when the mineral or crystal is isotropic, or if it be uniaxial and have its basal plane parallel to the microscope stage. If d be the distance in focussing between a selected point on the object and a point on the upper surface of the glass slip seen *through the object* at the same point, and e be the distance between the focussing of the same selected point and the focussing of a point on the slip beside the object seen *through the medium*, the ratio of the refractive index of the object to that of the medium will be equal to the ratio of e to d. In other cases the method is not applicable except with special precautions.

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